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Application of the TCO Method for the cement industry considering CCS sustainable technology.

Master Thesis in Business Administration International Business Consulting

By
Alejandra Barrera

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Supervisors:	Prof. Dr. Eng. Niklas Hartmann Msc.Hanhee Kim
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Declaration of Authorship

I declare in lieu of an oath that the Master thesis submitted has been produced by me without illegal help from other persons. I state that all passages, which have been taken out of publications of all means or unpublished material either whole or in part, in words or ideas, have been marked as quotations in the relevant passage. I also confirm that the quotes included show the extent of the original quotes and marked as such. I know that a false declaration will have legal consequences.

Offenburg, February 2023

Alejandra Barrera Acevedo

Preface

The adaptation of carbon capture technologies in accordance with cost-effectiveness makes it an attractive solution for cement manufacturers. The Total Cost of Ownership (TCO) method has become an essential tool for evaluating the feasibility and long-term value of such technologies.

The high-efficiency level of carbon capture that it provides not only reduces the carbon footprint of cement production but also leads to a decrease in taxes for CO_2 emissions. This contributes to making the cement manufacturing process sustainable and environmentally responsible, which is essential for the long-term success of the industry. By adopting innovative technologies like Oxyfuel, the cement industry can continue to produce the materials necessary for economic growth while reducing their impact on the environment.

Acknowledgment

I would like to express my sincere thanks to Prof. Dr. Eng. Niklas Hartmann for allowing me to be part of INES - Institute for Sustainable Energy Systems and his team to carry out this research. It was an enriching experience to work with you, and I deeply appreciate your specific and enriching contributions. Thank you for your human and professional warmth, which made this journey even more meaningful.

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I am pleased to dedicate this work to God, who opened the ways for my dreams to come true. "For with God nothing will be impossible" (Luke 1:37 NKJ). This verse has come true in my life, and I am grateful for His blessings.

I must thank with all my heart my Ma "Pollis", who is the best example of empowerment in my life, and my sister, who has always shown me unconditional love and complicity. Without her support, this achievement would not have been possible to both of you for being the blue sky on grey winter days. And off course also to the siblings that God has given me, Wil, Ariza & Tefy for his hole support and love.

> In Spanish: A mi Ma "Pollis" eres el mejor ejemplo de empoderamiento, "berraquera" en el argot colombiano; Hermanita por tu amor incondicional y complicidad, a las dos por ser el cielo azul en los días grises de invierno, ¡sin su apoyo esto no hubiera sido posible!; Y por supuesto también a los hermanos que Dios me ha dado, Wil, Ariza y Tefy por su apoyo y amor.

Finally, I want to thank my family and friends for your cooperation and constant support towards my goals. Your presence in my life fills my soul with joy.

Abstract.

Total Cost of Ownership (TCO) is a key tool to have a complete understanding of the costs associated with an investment, as it allows to analyze not only the initial acquisition costs, but also the long-term costs related to operation, maintenance, depreciation, and other factors. In the context of the cement industry, TCO is especially important due to the complexity of the production processes and the wide variety of components and machinery involved in the process.

For this reason, a TCO analysis for the cement industry has been conducted in this study, with the objective of showing the different components of the cost of production. This analysis will allow the reader to gain knowledge about these costs, in the industrial model will be to make informed decisions on the adoption of technologies and practices that will allow them to reduce costs in the long run and improve their operational efficiency.

In particular, this study pursues to give visibility to technologies and practices that enable the reduction of carbon emissions in cement production, thus contributing to the sustainability of industry and the protection of the environment. By being at the forefront of sustainability issues, the cement industry can contribute to the achievement of environmentally friendly technologies and enable the development of people and industry.

The Oxyfuel technology has been selected as a carbon capture solution for the cement industry due to its practical application, low costs, and practical adaptation to non-capture processes. The adoption of this technology allows for a significant reduction in CO_2 emissions, which is a crucial factor in achieving sustainability in the cement manufacturing process.

Carbon capture storage technologies represent a high investment, although these technologies increase the cost of production, the application of Oxyfuel technology is one of the most economically viable as the cheapest technology per capture according to the comparison. However, this price increase is a technical advantage as the carbon capture efficiency of this technology reaches 90%. This level of efficiency leads to a decrease in taxes for the generation of CO_2 emissions, making the cement manufacturing process sustainable.

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Nomenclature

AACE: Association for the
CAC: CO_2 avoided
ASU: Air Separation Unit
BAT: Best Available Technique
BREF: BAT Reference
CAC: Cost of Avoided CO_2
CaL: Calcium Looping
CAP: Chilled Ammonia Process
CCR: CO_2 Capture Ratio
CCS: Carbon Capture and Storage
CEPCI: Chemical Engineering Plant Cost Index CHP: Combined Heat and Power
clk: Clinker
COC: Cost of Clinker
CO_2: Carbon dioxide
CH4: Methane
CPU: CO_2 Purification Unit
EPC: Engineering, Procurement and Construction Costs
FGD: Flue Gas Desulphurizer
EECFA Eastern European Construction Forecasting Association
GT: Gas Turbine
GHG: Greenhouse gases
HRSG: Heat Recovery Steam Generator
KPI: Key Performance Indicator
LHV: Lower Heating Value
MEA: Monoethanolamine
N2H: Nitrous oxide
NOAK: Nth of A Kind
NF3: Nitrogen trifluoride
O&M: Operations & Maintenance
PM: Particulate Matter
R&D: Research and Development
RDF: Refuse Derived Fuel
SDG Sustainable Development Goals
SF6 Sulfur Hexafluroide
SPECCA: Specific Primary Energy Consumption for CO_2 Avoided
STP: Standard Temperature and Pressure
SNCR Selective non-catalytic reduction
TDC: Total Direct Costs
TEC: Total Equipment Costs
TEG: Triethylene Glycol
TOC: Total Organic Carbon
TOT: Turbine Outlet Temperature
TPC: Total Plant Costs
VPSA: Vacuum Pressure Swing Adsorption
WTE: Waste-to-Energy

1 INTRODUCTION

One of the Paris agreement's objectives states "to substantially reduce global greenhouse gas emissions to limit the global temperature increase in this century to 2 degrees Celsius while efforts are made to limit the increase further to 1.5 degrees"[1], with this agreement intrinsically nations commit to working to reduce emissions in a way that mitigates climate change, leading towards a :

According to the united nation climate change, the Climate Neutral Now Initiative encourages and supports organizations and other interested stakeholders to act to achieve a climate-neutral world by 2050" [2].

With the challenge of the country agreement, the German Federal Government aims at a 55% reduction of greenhouse gases by 2030 [3] by reducing the consumption of fossil fuels and implementing energy-efficient systems.

According to the European Commission, the cement sector needs for its production approximately the use of fossil fuels which in CO_2 emissions is 35% and the remaining 65% are indirect from the same process [4], this is why the implementation of carbon capture and storage technologies is required thus leading this industrial sector to a potential reduction of its CO_2 emissions.

In cement manufacturing technologies, Carbon capture technologies have a high cost compared to non-capture technologies, in this research selected Oxyfuel technology due technical and economic factors. The application of Oxyfuel technology leads to a rise in the price of cement per ton manufactured and the same time is the cheaper technology by capture. However, this price increase is a technical advantage as the carbon capture efficiency of this technology is as high as 90%. This efficiency level leads to a decrease in taxes for the generation of CO_2 emissions, making the cement manufacturing process sustainable.

To provide financial information to evaluate the cost of the product, where an approximation of the total cost that will be generated in the operational life cycle is presented, Total Cost of Ownership (TCO) is a method for calculating the total purchase cost [5]. This method considers all costs related to the product or service, including the initial purchase price, as well as fixed costs, such as maintenance labor and contingencies, The objective of TCO is to provide a more comprehensive understanding of the real cost of a product or service, which goes beyond the initial purchase price.

The study aims to evaluate technologies without carbon capture and storage carbon capture technologies available for the cement industry and understand their operation mechanism.

This study aims to identify sustainable technologies for the cement industry that can reduce environmental impact while maintaining economic viability. The TCO method will assess the total costs associated with cement production with and without CCS technologies. The study will analyze the impact of CCS on the TCO compared to non-CCS technologies. The research will also explore factors that influence the adoption of these technologies in the cement industry. The TCO model will present a quantitative cost analysis method to compare the cost differences between CO2 capture technologies, helping cement plants to make informed decisions and adopt the most cost-effective and efficient solution. The ultimate objective is to provide the necessary information about production costs in the cement industry to reduce its carbon footprint in an economically viable way. The research aims to examine the various costs associated with the operation of a cement plant. The focus is on the investment, variable costs, and fixed costs, critical components in determining the TCO.

It is worth noting that transportation costs and taxes are excluded from the analysis. This decision is based on minimizing operating expenses by building cement plants in areas close to the source of raw materials, thereby reducing transportation costs.

However, it is essential to acknowledge that the logistics cost can vary significantly, even when the cement plants are near the raw material source. The variations in logistics costs can result from several factors, such as the distance of distribution, the type of transportation used, and other related variables. Therefore, it is crucial to consider these factors when evaluating the overall cost structure of the cement plant operation.

There are five primary components to this study. The first is the recent introduction, which attempts to take the reader through the study subject.

The second section reviews the research literature, separated into references to global climate targets, information on the cement business, an overview of the systems necessary for cement manufacture, and carbon capture methods.

The third section is an illustration of the TCO method, which shows the method and the data collected in order to give way to the fourth section, which shows the method's results, in this case the cement manufacturing cost data with and without carbon capture technology, with an appreciation of the results and a comparison of two scenarios.

The study's conclusions are presented in the fifth section, focusing on how the obtained results address the research questions and offering recommendations for future studies, whether to enhance current findings or suggest new ones.

Hence Research questions:

- What are the different technologies that the cement industry can adopt to reduce its greenhouse gas emissions?
- Is the implementation of CCS technologies necessary in the cement industry?
- What is the total cost of ownership (TCO) without CCS for the cement industry compared to the TCO of CCS technology?
- What are the factors that influence the adoption of without CCS technologies and CCS technology in the cement industry?

Significance: his study aims to a research gap regarding the analysis of the most influential factors within the Total Cost of Ownership (TCO) method. While previous research has conducted general comparisons depending on their industrial or research focus, there remains a lack of detailed examination of these critical factors. This research highlights these specific points throughout the analysis and emphasizes their significance in the context of the scenarios proposed. By doing so, this study will pave the way for more in-depth investigations into the application of the TCO method to the cement industry, with a focus on identifying key factors that drive costs and exploring potential solutions for cost reduction. Therefore, this research aims to bridge the existing research gap and provide a foundation for further analysis of the TCO method as it applies to the cement industry mentioned in the recommendation chapter.

2 FRAMEWORK

2.1 Global climate targets

The global sustainability agenda issued by the United Nations in 2015, also known as the 2030 Agenda for Sustainable Development, is a comprehensive plan consisting of 17 Sustainable Development Goals (SDGs) and 169 targets. The agenda was developed to provide a model for sustainability at a global level, addressing social, economic, and environmental challenges facing the world [6]. Of the SDGs, climate change is one of the most pressing issues. Greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, are the primary cause of climate change. These gases trap heat in the Earth's atmosphere.

Over the last 150 years, industrialization, deforestation, and large-scale agriculture have caused greenhouse gas levels in the atmosphere to reach record levels not seen in three million years. As populations, economies, and living standards increase, so do the cumulative greenhouse gas emissions[7]

In order to reduce greenhouse gas emissions and slow down global warming, the global sustainability agenda requests a range of actions at the international, national, and local levels. These include the transition to renewable energy sources, improving energy efficiency, reducing deforestation, and promoting sustainable agriculture and land use, which is the focus of this research work [8]; this is related to objectives seven, nine, and thirteen.

Figure 1: Objective 7, 9 &13. Affordable, clean energy; Industry, innovation, and infrastructure; Climate actions [9] (p 14).

Achieving the goals defined in the global sustainability agenda requires By taking action to reduce greenhouse gas emissions and address climate change, we can help create a more sustainable and durable future for all[7].

The results report of UN 2022 shows that the demand for fossil fuels such as coal, oil, and gas increased and consequently CO2 emissions also increased, reaching very high levels, this is correlated with the cement industry by the fossil fuel that it uses. [9]

Figure 2: Carbon dioxide emissions from energy combustion and industrial processes,1900–2021 (Gigatons of CO_2) [9] (p 52)

[6]World leaders meeting at the United Nations Climate Change Conference (COP21) in Paris to address climate change and its adverse effects reached a historic agreement: the Paris Agreement.

The Paris Agreement, in effect since 2016, aligns with the Sustainable Development Goals and aims to limit global temperature increase to below 2°C this century. It also aims to enhance the capability of countries to implement, adapt and acquire technologies to combat climate change [1].

The desired scenario is to reach zero emissions in 2050, where different economic and technical contributions must be made globally to achieve it. The graph shows the global scenarios according to those mentioned above.

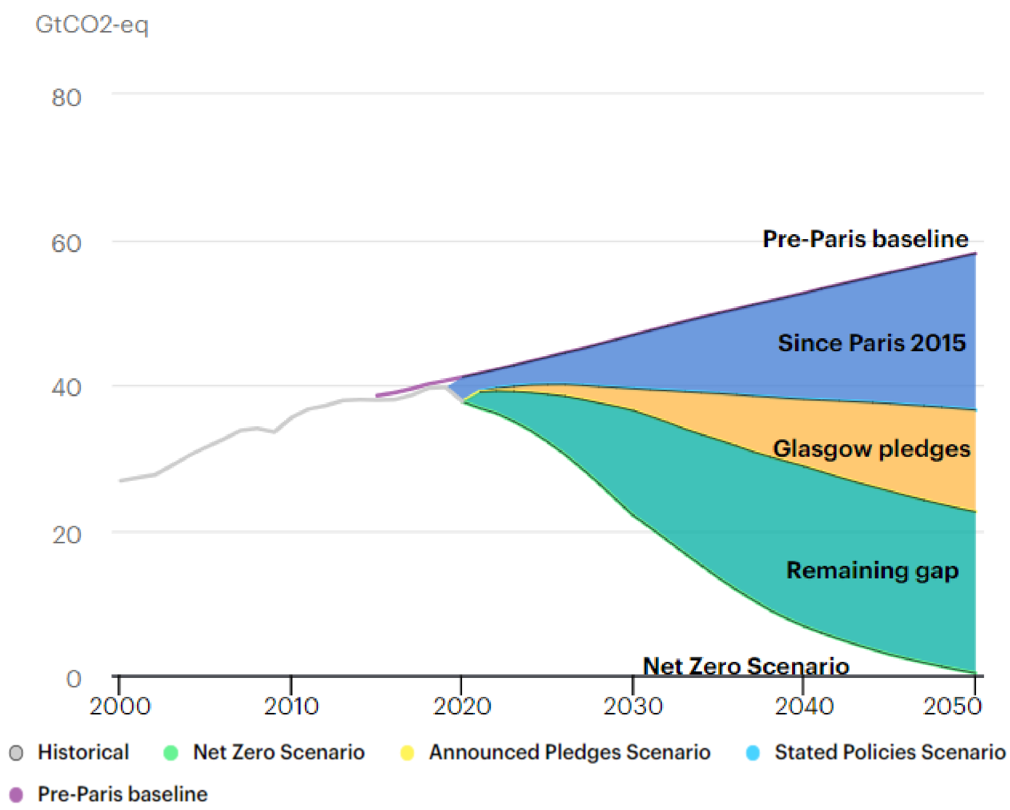


Figure 3: Global emissions scenario, 2000-2050 [10]

2.2 Cement industry framework

Across history, cement has served as the primary building material utilized by humanity, as Portland cement and its derivatives are essentially comprised of a combination of minerals such as limestone, clay, and gypsum, which are widely available in nature [11].

Cement is a primary building material that is widely used in construction projects all over the world. It is made from a mixture of different minerals that are heated and processed to produce the key ingredient in cement Clinker, produced by the calcination of limestone, clay, and iron ore.

People not directly involved in the construction industry often confuse "cement" and "concrete." Cement is a powdered material mixed with water, sand, and gravel to form a solid concrete mixture. Concrete is used to construct structures such as buildings, bridges, and roads.

Cement can also be mixed with water, lime, and sand to form a softer mixture called mortar. Mortar is used to bind bricks and other building materials together.

In short, cement is a powdered material used to make concrete and mortar. Concrete is the solid material used to build structures, while mortar is used to bind building materials together.[12]

From the mixture of minerals such as limestone, clay, and iron ore, after the calcination of these materials, a synthetic material called Clinker is obtained, which will be the predominant raw material together with other chemical additives to obtain what we know as cement. Depending on the application its properties are modified according to the mixture of additives to modify properties such as strength, durability, or aesthetics; the standard and will be used for the present study is Portland cement.[11]

The table below shows the minerals of which Clinker is composed.

Raw meal composition at preheater inlet		
Parameter	**Value**	**Unit**
CaO	43.22	wt%
CO_2	34.74	wt%
SiO_2	13.8	wt%
Al_2O_3	3.25	wt%
Fe_2O_3	1.96	wt%
H_2O	1	wt%
MgO	0.71	wt%
K_2O	0.55	wt%
SO_3	0.34	wt%
Na_2O	0.12	wt%
TOC	0.1	wt%
TiO_2	0.06	wt%
Mn_2O_3	0.05	wt%
Sulphide$_{1)}$	0.05	wt%
P_2O_5	0.04	wt%
Cl	0.01	wt%

Figure 4--Raw meal composition. [27]

2.3 Cement in the global and European Markets

According to the CEMBUREAU report published in 2021, approximately 4.1 billion metric tons of cement consumed worldwide in 2020. It is vital to note that cement consumption varies greatly depending on the country and the region. The leading producers are the USA, China, India; and the CEMBUREAU members contributing 6.1% of global production and the EU27 representing 4% [12].

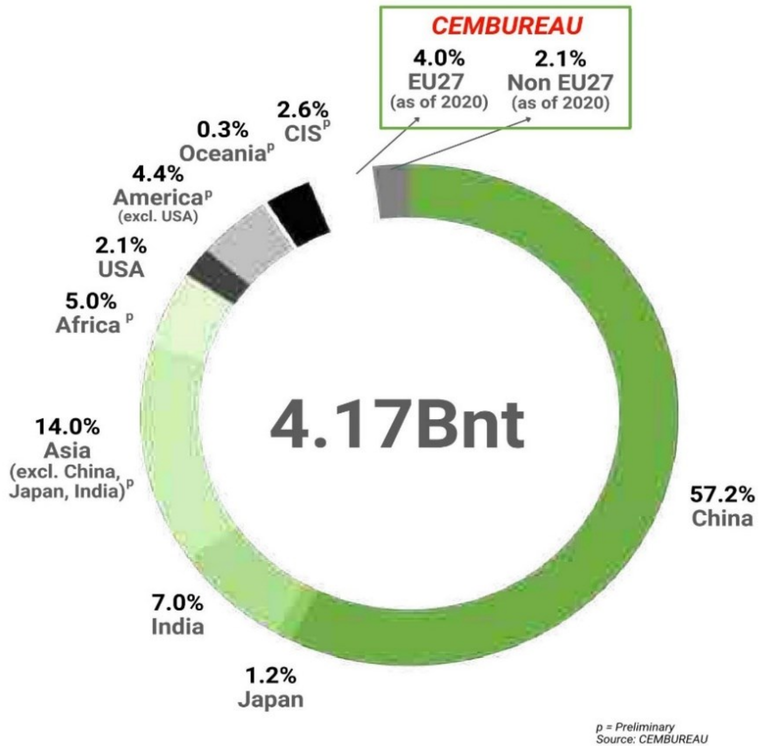


Figure 5: World cement production 2020, by region and main countries, % Estimations[12]

The cement industry in Europe for 2021 achieved the switch from fossil fuels to alternative fuels, thus advancing one of its carbon neutrality targets. However, unfortunately, the scenario is different worldwide, even though the rate of increase has lately been moderated, primarily because of a larger worldwide Clinker-cement share. Due to the pandemic, to the fact that the crisis equally impacted not all nations, the speed, severity, and time of the recovery have varied greatly from one nation to the next. CEMBUREAUR results reveal that the building industry greatly aided the entire economy's revival [12].

The building volume in the Euroconstruct (Europe's leading construction market forecasting network) region is predicted to increase by 3.6% in 2022, and the outlook is still promising for 2023 (+1.5%) and 2024 (+1.2%). Regarding the recovery's pace, the Euroconstruct region's total construction production already surpassed the pre-corona level of 2019. This is expected to expand to €1.84 trillion by 2024, a 7% increase from 2019. The construction market in the EECFA region is predicted to increase by 2.8% in 2022 and 1.2% in 2023. Nevertheless, most Euroconstruct and EECFA nations anticipate positive development in 2022 and 2023. [12]

The industry established the European Cement Research Academy (ECRA) in 2003 to coordinate and streamline its research activities. ECRA comprises over 47 leading cement producers worldwide and is dedicated to facilitating and accelerating innovation in the sector [13].

Cement producers engage in R&D activities with a range of stakeholders, including universities, research institutes, customers, equipment suppliers, and start-ups. Additionally, individual cement companies invest in research and innovation to drive their own product and process advancements [13].

Due to the global objectives of sustainability and environmental policies, Europe has developed two mega projects between companies and including universities for the implementation of clean technologies in the manufacture of cement, the projects are called CEMCAP where the implementation of CO_2 capture technologies on a large scale is being prepared, in this case the most important partner is the German cement company Heidelberg and companies of its group. On the other hand, there is the LEILAC project, which seeks to develop a technology through research into capture technologies that allows 95% of carbon capture in a way that the capital costs are minimal [13].

The German Cement Works Association (Verein Deutscher Zementwerke-VDZ) provide information of due to the high cost of truck transportation; bulk cement is mainly supplied to local markets. Production facilities in the German cement industry are distributed throughout the Federal Republic of Germany based on appropriate mineral resources and located in the vicinity of the respective limestone deposits. In 2020, 21 companies with their 54 factories produced around 35.5 million tons of cement in Germany, see figure 7. [14]

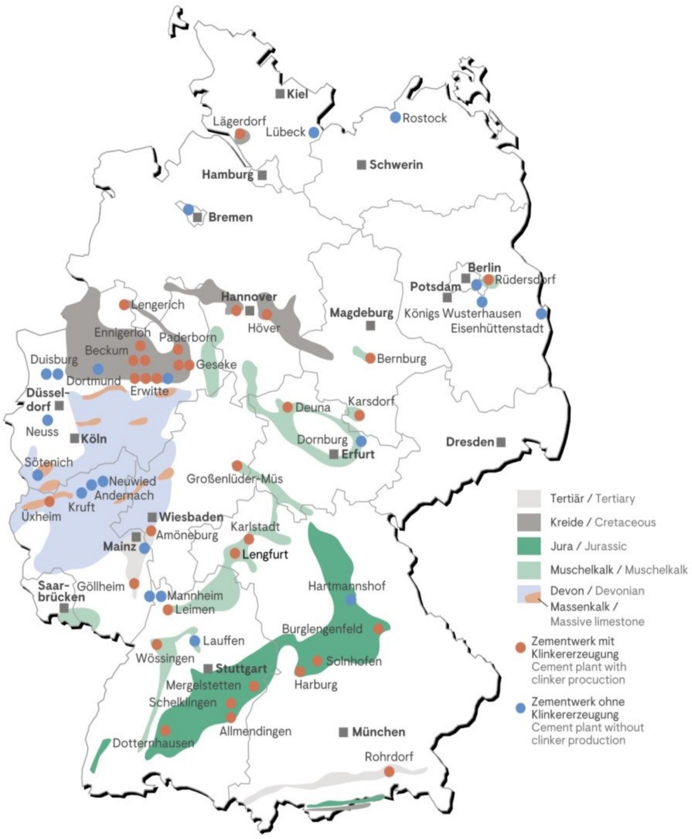


Figure 6: Cement works in the Federal Republic of Germany. [14]

2.4 Cement process generalities

About the cement process, it is essential to note that there are distinct types of manufacturing or processes to manufacture cement denominated dry and wet, and once intermediately is semi-wet.

Cement manufacturing processes have undergone many changes over the years, as manufacturers strive to find more efficient and environmentally friendly ways to produce cement.

The first cement plants were dry plants, meaning that the raw materials were ground and blended without the addition of water. This method was simple and inexpensive, but it had several drawbacks. One major issue was that the process generated a lot of particulate matter, which had negative environmental impacts. Additionally, a significant percentage of the product was lost in the form of dust and fines [15].

To address these issues, cement manufacturers developed the semi-wet process. This method adds a small amount of water to the raw materials to create a slurry that is ground and homogenized. This process reduces the amount of particulate matter released into the environment and helps to retain more of the product, as the water binds the materials together.
Later, the wet process was developed. This method, the raw materials are mixed with a larger amount of water to create a "paste." The paste is then ground and homogenized, and the resulting slurry is fed into a kiln. The wet process has several advantages over the semi-wet process. For example, the paste is easier to handle, and the water helps to regulate the temperature in the kiln. Additionally, the wet process results in a more uniform product, as the paste is better mixed than the slurry in the semi-wet process [15].

However, the wet process also has some disadvantages. It requires a significant amount of energy to dry the product after it comes out of the kiln, and the water used in the process can be a source of pollution if it is not treated correctly. The choice of which cement manufacturing process to use depends on various factors, including the availability of raw materials, energy and water resources, and environmental considerations.

Overall, this next image provides a quick and easily understandable reference for the layout and distribution of equipment in a cement plant, In the case of a cement plant, which may have a large number of different equipment and processes, having a visual reference can quickly identify different equipment and understand how it is distributed throughout the plant[16].

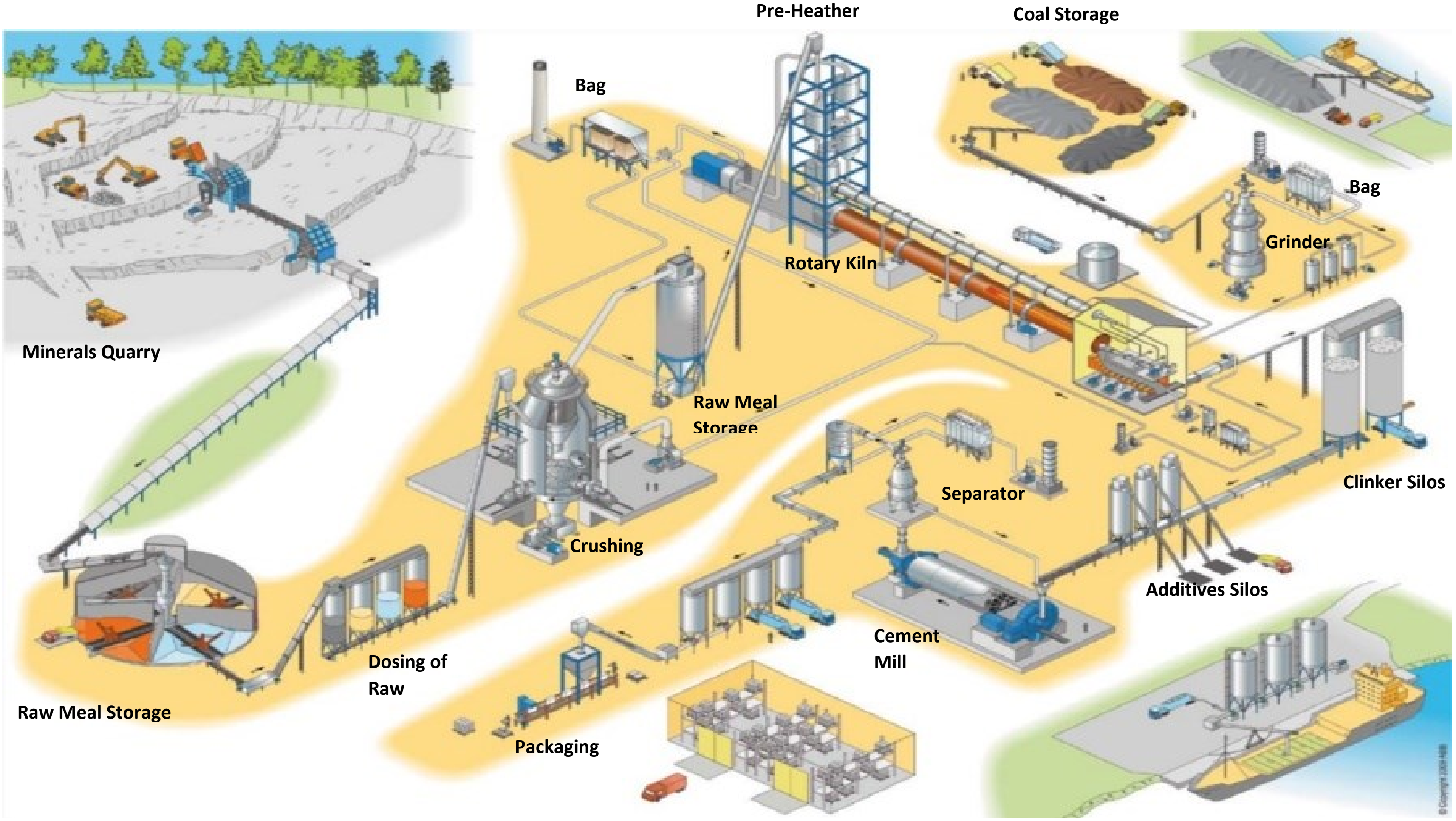


Figure 7: Typical layout of a cement plant [16]

The following diagram illustrates the cement manufacturing process in a graphical way after the theorical explanation.

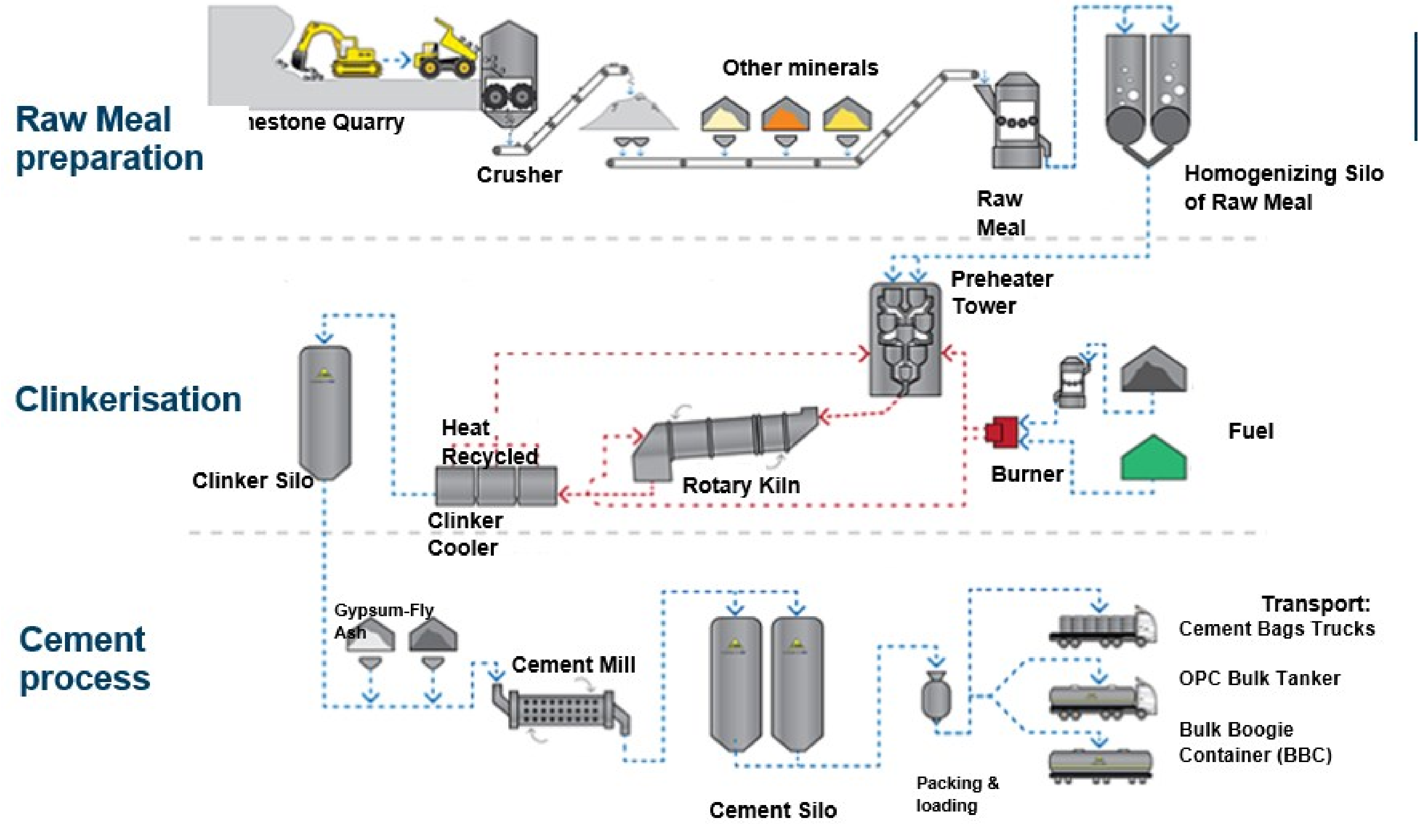


Figure 8: Process division in cement manufacturing. [17]

The manufacture of cement involves several technical terms that are specific to the industry. The three main stages of cement production are:

- Raw material preparation.
- Clinker production.
- Cement grinding and distribution.

Stage of raw material preparation

The explanation of the cement process is based on information from the Spanish Cement Manufacturers' Association [11].

Quarrying

The raw materials are minerals found on the Earth such as limestone, clay, shale, sand, and iron ore. In the places where they are found, controlled explosions are generated to obtain stones of a smaller size. In the case of clay and marls, backhoes are used for extraction.

Crushing

A crushing process is carried out to obtain a manageable particle size for the plant's equipment. The material is transported employing of conveyor belts.

Grinding and Pre-homogenization

The material from the shredding process is stored in layers to create a more uniform mixture. The material can then be metered as required for further processing.

Clinker production

Preheating and Calcination

This process involves a series of cyclones through which the raw material mixture passes. These cyclones direct the material flow in one direction and the hot exhaust gases in the opposite direction, allowing the combustion gases to preheat the mixture.

It is worth noting that during this stage, the hot gases are generated by the furnace process and come with recoverable heat. The heat recovery efficiency can be enhanced by performing recovery at each stage.

In essence, preheating is a crucial step that facilitates the firing of the raw material. It is achieved by utilizing the heat generated by the furnace process in the cyclones. In this process the temperature can rise to approximately 850ºC.

The process of transforming limestone into lime is known as calcination. In contemporary manufacturing facilities, a major part of the high-temperature reaction occurs in a combustion chamber called the pre-calciner, located at the bottom of the pre-heater before the kiln. In contrast, the remainder of the reaction takes place in the kiln.

Kiln (Rotary Kiln)

This is the rotary kiln where the raw material is cooked at a temperature of 1500ºC, the raw material advances inside the kiln in the direction of the flow and the temperature increases, which is where the chemical reactions-calcination- that allow the Clinker to be obtained take place.

A rotary kiln is a long cylinder rotating about its axis that rotates slowly about its axis. It is tilted slightly towards the outlet so that materials flow steadily from the inlet to the outlet.

The raw materials enter the cooler end of the kiln and are gradually heated as they move toward the hotter end. During the process, the materials are subjected to high temperatures and converted into Clinker.

Clinker Cooling

The product known as Clinker, an artificial material, is obtained upon exiting the kiln. In this process, the material must be cooled from approximately 1400ºC to 100ºC. Cold air is introduced from outside to achieve this descent, and the hot air resultant is reused by taking it to the preheating.

The cooling process enhances the Clinker's quality, increases the cement grinding's productivity, reduces heat loss, and facilitates transport and storage.

Clinker Storage

The storage of Clinker preserves it is characteristics; therefore, the storage should ensure water resistance, controlled temperature, and not affected by the material's own embrittlement.

Cement grinding and distribution

Cement proportional and grinding.

In this process, the mixture comprises Clinker, the primary material, and additives such as gypsum. The mixture is transported to a grinding.

Mills can be either roller or ball type. The latter, and most used, consists of a large tubular structure that rotates on its axis and contains abrasive spheres within. As the mill rotates, the spheres collide, crushing the cement and additives to produce a fine and homogeneous powder known as cement.

Cement storage, packing and delivery.

Cement is stored in silos depending on its type. These silos are tall, cylindrical structures made of steel or concrete, with a capacity ranging from a few tons to several hundred tons. They are designed to keep cement dry and free from moisture, which can cause it to harden and become unusable. The silos are equipped with special equipment, such as filters and ventilation systems, to maintain the quality of the stored cement.

Cement can be sold in different presentations, depending on the needs of the customer and the intended use. One common way of packaging cement is to use an injection machine to fill 25 kg bags with cement powder. These bags are commonly called to as "25 kg bags of cement" and are often used by smaller construction projects. Some cement manufacturers may also mix the cement powder directly at the factory and ship it in a ready-to-use form. In this case, the cement is typically transported in specialized cement mixers, which can deliver the ready-mixed cement directly to the construction site. This method is often used in large-scale construction projects, where time and efficiency are critical.

2.5 CO_2 emissions

Clinker production emits a significant amount of CO_2 due to the chemical process that takes place during production. Clinker is a major component in cement production, and is produced by heating a mixture of limestone, clay, and other materials at high temperatures in a cement kiln. During this process, a chemical reaction known as calcination occurs, which involves the release of carbon dioxide (CO_2) from the limestone [18].
In addition to the calcination of limestone, clinker production also involves the use of fossil fuels such as coal, oil, and natural gas to heat the rotary kiln. This also contributes significantly to the CO_2 emissions associated with clinker production [18].

At present, CO_2 emissions arise from the utilization of fossil fuels, namely oil, coke, and coal, to generate the required heat in the process. Additionally, co-processing involving the utilization of alternative fuels obtained from an industry's processes has been introduced as a supplementary measure by some industries to curtail their reliance on fossil fuels; The graph shows some of the percentages reported by the WBCSD - World Business Council for Sustainable Development [4]:

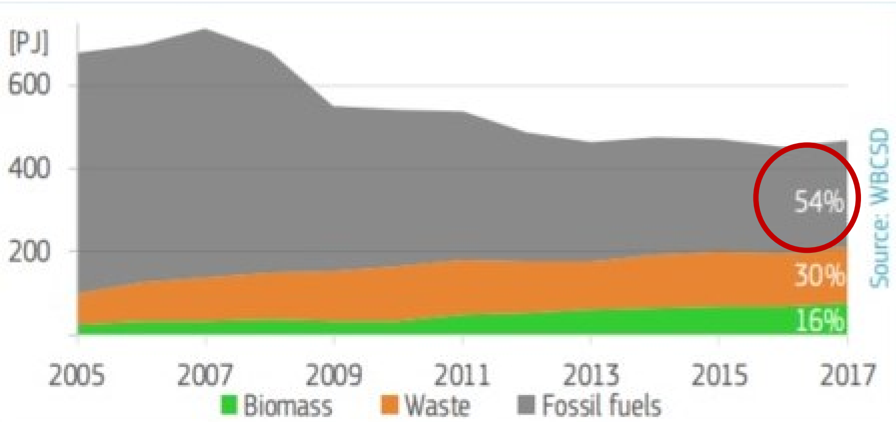


Figure 9: Thermal energy consumption by fuel in the EU cement sector.[4]

In line with global initiatives, the cement industry must also monitor its emissions to achieve a reduction of CO_2 emissions.

McKinsey Consulting shows the graph below which indicates that the cement industry generates ¼ of all CO_2 emissions in the industry and thus also the highest amount of CO_2 emissions per dollar of revenue because these emissions result from the calcination processes that occur in the Clinker production process [19].

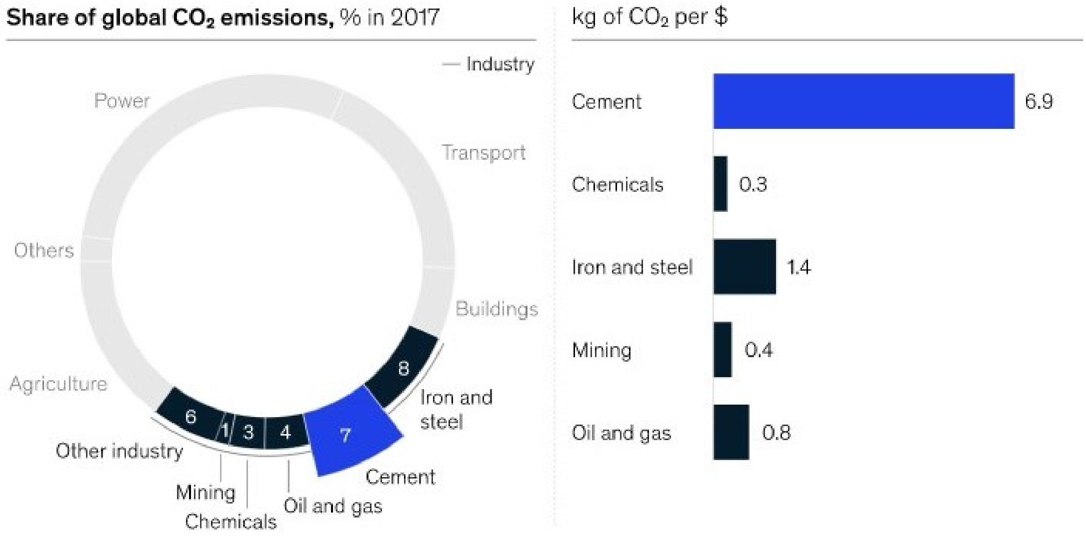


Figure 10: CO_2 emissions from cement production [19]

Based on the information provided, the consultant presented an image showing the critical sections of the cement manufacturing process where the highest energy consumption and CO2 emissions are generated. These sections are pre-homogenization, pre-calcination, and calcination, which transform raw materials into Clinker products.

These three processes are known to be energy-intensive and emit significant amounts of CO_2, making them a key focus for efforts to reduce the environmental impact of cement production. By identifying these sections as areas of high energy consumption and emissions, the consultant may be provide insights that could help inform efforts to develop more sustainable and environmentally friendly cement manufacturing practices. [19].
Due to the elevated temperature that the equipment must reach for the process, the furnace is fuelled with coal-fuel.

The Figure 12 gives a quick overview of the consumption and CO_2 emitted in the process including assumptions such as:

The assumed the world average, data from the world cement and concrete association, matching number 2017.
Assumed alternative grate cooler with 5Kh/t Clinker.
Assumed average truck transport of 200 km.

By the graph is possible to observe the energy consumption and CO_2 emissions throughout the production process of cement. The graph indicates that the energy consumption is low in the initial stages of the process, but it significantly increases in the Clinker process.

Starting from the preheater stage, the energy consumption increases as the material moves towards the pre calciner and then further to the calciner stage. The highest energy consumption is observed in the pre-calciner through calciner stage, which jumps from 100 MJoule/ton to 3150 MJoule/Ton.

It is also noteworthy that there is a direct correlation between energy consumption and CO_2 emissions. As energy consumption increases in the Clinker process, the CO_2 emissions also increase proportionally. The CO_2 emissions go from 17 CO_2 kg/ton to 479 CO_2 kg/Ton, which is a significant increase compared to the emissions in the previous stages of the process.

The graph shows that cement production's energy consumption and CO2 emissions are significantly higher in the Clinker process, particularly in the calciner stage.

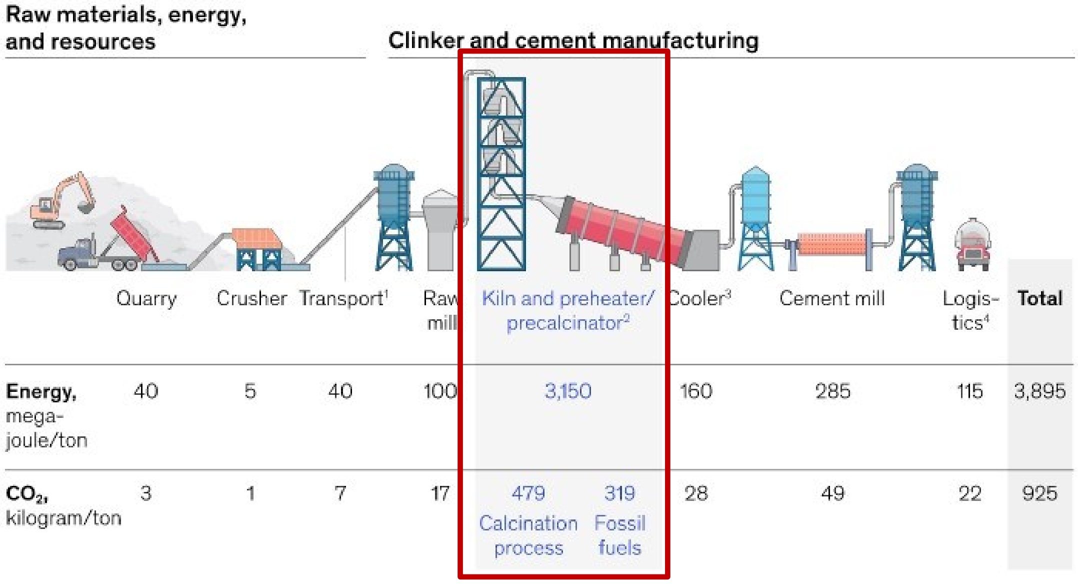


Figure 11: Cement process energy consumption and emission [19]

Due to the high CO_2 emissions, the cement industry is one of the most pressured industries by investors and governments, which in parallel means that more supportive policies must be generated for this industry so that it can implement the use of other technologies that will help it to follow the zero-emission target.

The consultancy has created a graph that shows two scenarios: one with expectations and the other where nothing is done to reduce emissions.
Generally, it is anticipated that CO2 emissions in 2050 will align with cement demand, resulting in a slight increase to 2.9 GtCO2. However, there will be variations in emission reduction potential among different regions due to country-specific regulations, consumption patterns, and local industries' efforts to decarbonize. China is expected to benefit from reduced demand and plans to improve operational efficiency and technology to decarbonize. Southeast Asia and India have begun to establish policies that support decarbonization, such as India's market-based mechanism that targets energy efficiency in cement plants. Nevertheless, emissions reduction efforts in these regions may be counteracted by urbanization and economic development, leading to a rise in cement demand.

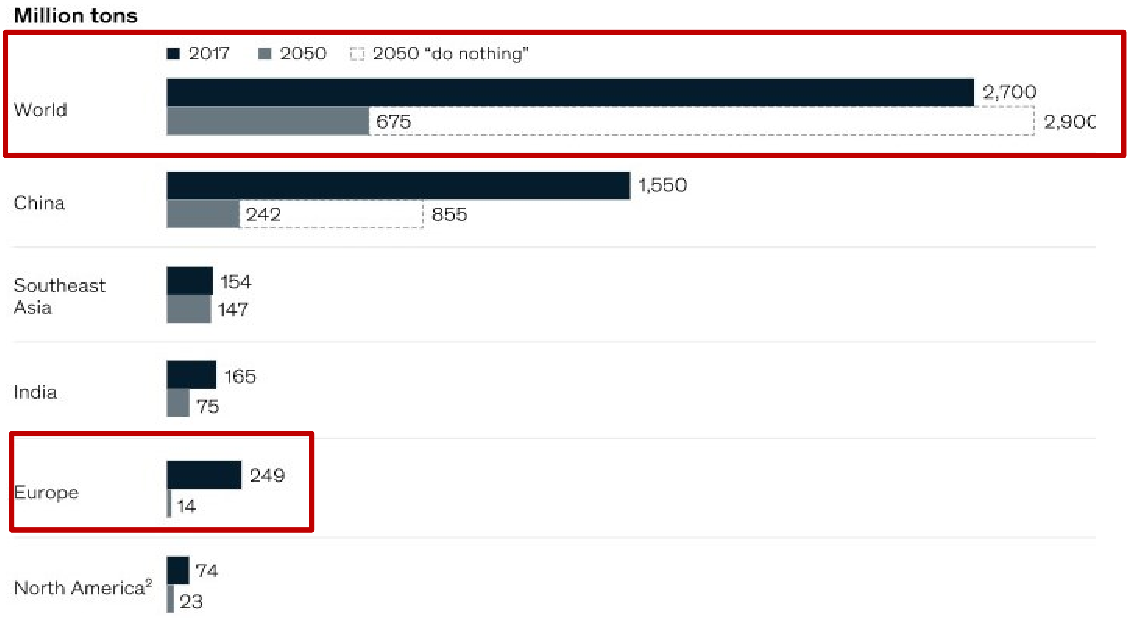


Figure 12: CO_2 emission scenario 2050. [19]

2.6 Technologies for Decarbonization in The Cement Industry.

Decarbonization is the process of reducing the amount of carbon dioxide (CO_2) emissions released into the atmosphere, which can be achieved by adopting of clean technologies that allow the generation of energy without producing greenhouse gas emissions.
Below are some possible technologies that can be used for decarbonization:

- Electrification of heat.
- Hydrogen for heat.
- Carbon Capture storage (CCS) & utilization (CCU).
- Low carbon cements.

2.6.1 Electrification of heat

Electrification refers to the use of equipment or systems that use electrical energy and this being transformed into thermal energy, at present the cement industry is exploring technologies such as plasma generators, microwave energy, technology to electrify cement kiln heating process, Nevertheless, these technologies are still in the research and pilot testing stages. [4]

“Power-to-Heat (PtH) is the term used to describe energy conversion technologies, in which electrical power is specifically transformed into heat and thus represents a coupling between the electricity and heat sectors.” [20]

2.6.2 Hydrogen for heat

Fuel cells generate electricity by converting hydrogen into electricity, while electrolysis involves splitting water into hydrogen and oxygen using electricity, which occurs in a device known as an Electrolyzer, Nevertheless, it has yet to be tested and is still under research.

Overview Electricity and Hydrogen for thermal energy supply	
Technological maturity	**Early demonstration** stage for plasma torches in Clinker manufacture. **Several Technological barriers** such as short operating life of the torch, difficulty with reproducing conditions and lack reliability of electric power sources
Economic Feasibility	Future feasibility dependent on electricity/hydrogen prices Current pilots show doubling of production cost for cement, although this ultimately entails only ~2% increase of finished infrastructure.
Key barriers	Use of plasma torches in Clinker manufacture would require substantial refurbishment of existing kilns. Technical considerations of hydrogen heating capabilities Current cost of technology
Recent progress	Several demonstration projects worldwide and in European Union

Figure 15: Overview of electrification and hydrogen for thermal energy supply as a technology option, incl. scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S) [21]

2.6.3 Carbon capture storage (CCS) & utilization (CCU)

Capture and storage technologies can be integrated into factories either as retrofitting measures or by modifying existing processes and equipment. The aim of such technologies is to capture CO_2 emissions generated during combustion and production processes, and prevent them from being released into the atmosphere. [4]

In the case of Carbon Capture and Utilization (CCU), captured CO_2 can be utilized within the same industrial process, or it can transported for use in other industries or applications. Alternatively, it can be injected into deep geological formations such as depleted oil and gas fields or saline aquifers, where it can be securely stored for the long term [4].

Carbon Capture and Storage/Utilization (CCS/CCS)	
Technological maturity	**Early demonstration** stage for CCS/CCU application in Clinker and cement production. **Near zero-emission option** considering the highest achieved capture rate of single applications has been around 90% as 2020.
Economic Feasibility	**Hight projected cost** of capture process emissions at full scale of 50-70 E/tCO_2, without including any cost estimates for CO_2 transportation and storage. **Other estimates** assume CAPEX investments per ton CO_2 of 150 EUR in 2030 and 111 Eur in 2050 for capturing processes, as well

	as140 EUR in 2030 to 113 EUR in 2050 for transportation and storage. **Limited opportunity** for CCU due to disadvantageous combinations of product value, increased energy demand from the conversion process and market size of the product.
Key barriers	**Transportation and storage** of captured CO_2 critically important for applicability of CCS/CCU technology in cement making process, for example identification of storage sites in the proximity to cement sites. Further, permanence issues may appear related to the storage of captured CO_2. **Carbon capturing requires high electricity demand** of 220kWh/tCO_2, which makes decarbonization of electricity supply crucial. In some cases, there will also be an increased thermal energy demand.
Recent progress	**Several demonstration projects worldwide and in European Union.** Global CCS institute database list lists seven completed or ongoing CCS pilot projects as of June 2020 worldwide. Plans for additional plant in Norway with 400.000 tons CO_2 captured annually. **Several research programs and consortiums** ongoing such as: Catch4climate by four major cement procedures to investigate de Oxyfuel CCS technology in the cement production process. Westküste 100 to investigate the utilization of captured CO_2 from cement making process un–Northern Germany to produce low-carbon aviation fuels. CEMCAP project and LEILAC project funder under horizon 2020 program to CCS technology.

Figure 16: Overview of Carbon Capture and Storage/Utilization (CCS/U) as a technology option, including scenario assumptions for High Innovation Capture Scenario (HIC-S) and High Innovation Processes Scenario (HIP-S) [21]

2.6.1 Low carbon cements

Work is underway to develop alternative Clinkers emitting less CO_2 than Portland cement. However, the application and diffusion of these alternative Clinkers are limited by barriers on the supply side (such as availability and cost of raw materials) and in terms of quality specifications.

One way to reduce the energy required to produce Clinker and the associated emissions is to use supplementary cementitious materials such as fly ash and blast furnace slag.
These materials can partially replace Clinker, but their availability may decrease in the future depending on changes in the energy and steel sectors.

4 TECHNOLOGIES ANALYSIS

4.1 Definition of scenario-Technologies Analysis.

In the second chapter of the present work, we establish a connection between the overarching vision that underlies the study's objectives, and the specific research needs that arise from it. This chapter presents a detailed methodology showcasing various technologies that can satisfy industrial demands for mitigating CO2 emissions.

4.1.1 Reference plant

The term "reference plant" refers to a technology developed without considering the current imperative to reduce CO_2 emissions, and thus does not include CCS capture.

Data acquisition

The information has been compiled from diverse sources, based on technical research on the need for manufacturing materials, process facilities and other required components which are explained in the cost components section.

The CEMCAP Framework Document has established a reference cement plant, known as a Best Available Techniques (BAT) plant, for conducting various comparative evaluations [18,22].

This plant is composed of a dry process kiln that utilizes a five-stage cyclone preheater, a pre-calciner with tertiary air duct, and a grate cooler. Additionally, the plant is equipped with technologies for reducing emissions, including SNCR (Selective Non-Catalytic Reduction) technology, a dry additive process for SO2 reduction, and a modern dust filter [23].

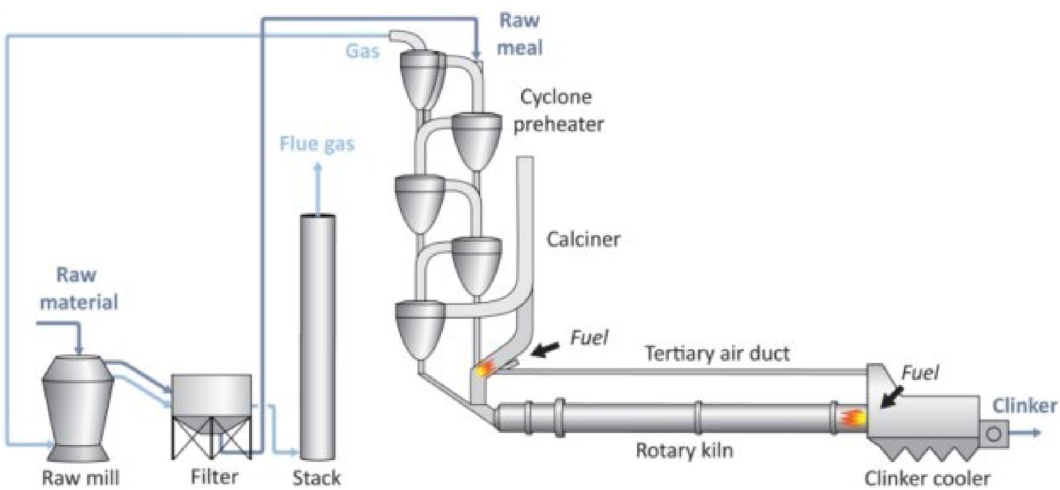


Figure 13: Flow sheet of the kiln system in a reference cement plant.jpg [23]

4.1.2 Leilac

Low Emission Intensity Lime and Cement is a technology that has been developed with the aim of separating CO_2 emissions from industrial processes in a simple and efficient manner. This is achieved using an indirectly heated calciner kiln, which serves to thermally decompose limestone, producing lime and CO_2. The CO_2 is then separated from the process gases using a process called carbon capture, which allows for the capture and storage of CO_2 emissions [24,25].

One of the advantages of Leilac is its compatibility with greenfield and retro field projects ash the figures show, where it can be easily integrated by installing tubular modules depending on the configuration of the rotary kiln. This means that the technology can be implemented in new industrial facilities without significant modifications to the overall plant design. [25]

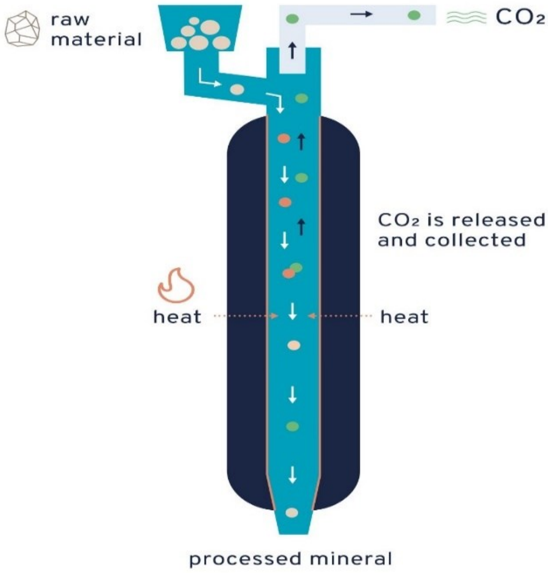


Figure 14: LEILAC- Principle [25]

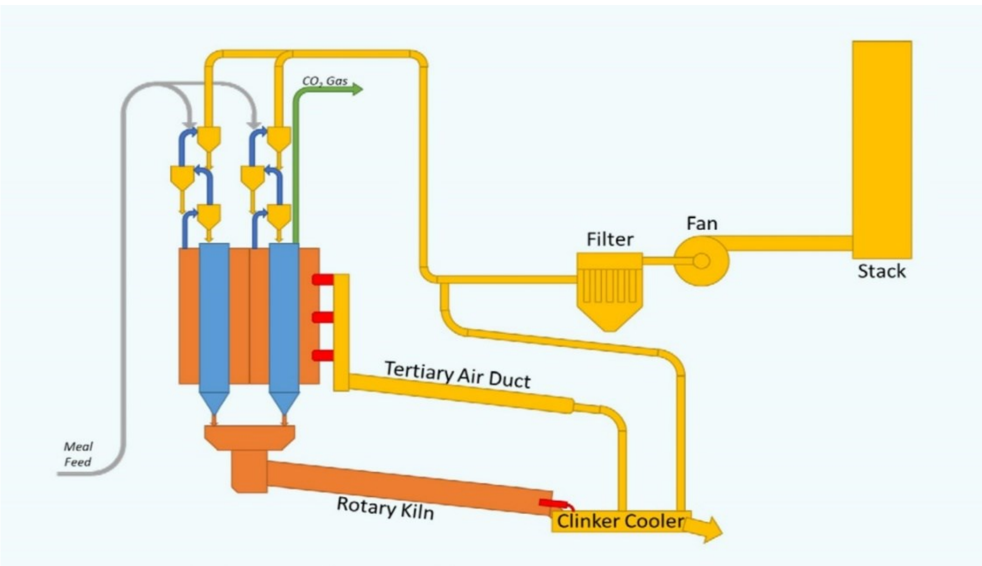


Figure 15: Flow Diagram of a full LEILAC installation [25]

[23]The following section outlines the technologies that are relevant for the comparison as per the CEMCAP project.

4.1.3 MEA absorption

The technology called MEA (Monoethanolamine) is a method of capturing CO2 through a chemical absorption process that involves using aqueous amine solutions as solvents. MEA is the most used amine, and it has been applied in various industrial sectors, providing a wealth of operational knowledge. The MEA plant can be installed as a post-combustion process after the dust filter and before the stack, without requiring any modifications to the cement kiln. In order to minimize solvent degradation, effective emission reduction technologies for NOx and SOx must be installed in the kiln. Steam is necessary for solvent regeneration, which can be generated at the plant or brought in from an external source.

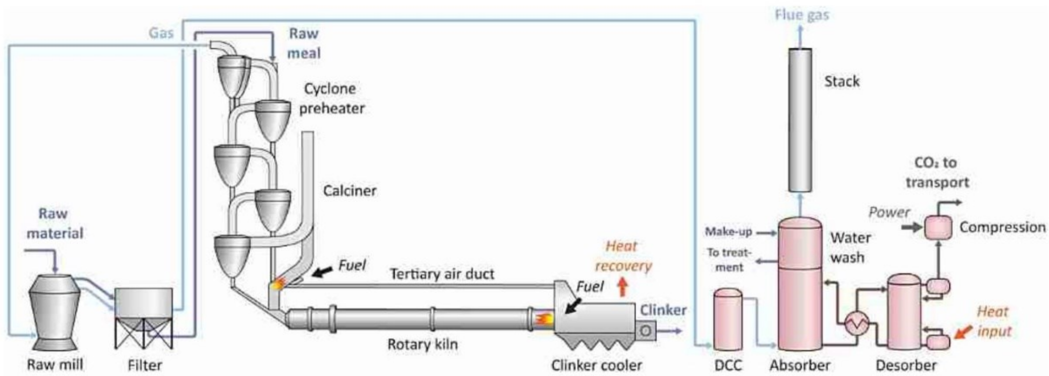


Figure 16: MEA process for CO2 capture at a cement kiln [23]

4.1.4 Oxyfuel process

The oxyfuel technology uses a mixture of pure oxygen and CO_2 gas instead of regular air to fuel combustion in a kiln. Nitrogen is removed from the air using an air separation plant before it is supplied to the kiln, resulting in a higher concentration of CO_2 in the flue gas. In order to maintain an appropriate temperature, some of the flue gas is recycled in the previous process. The flue gas leaving the oxyfuel cement kiln is purified and compressed in a CO_2 purification unit.

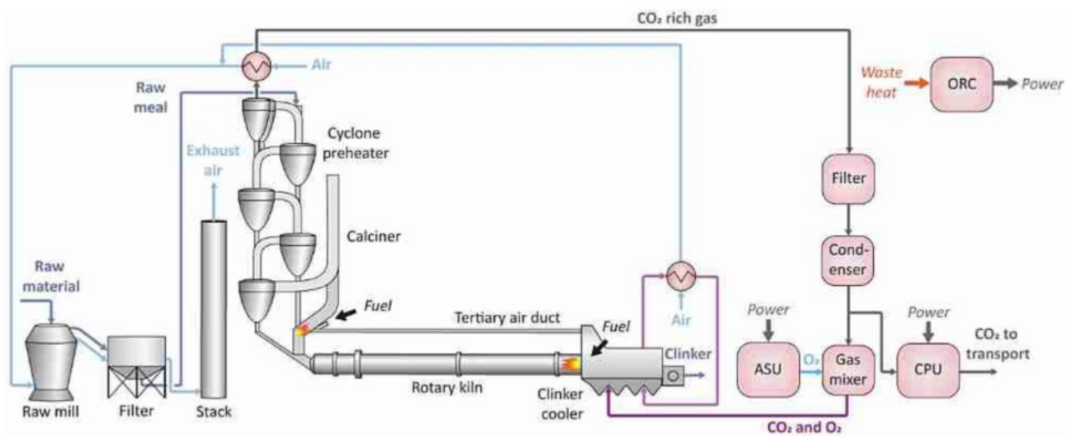


Figure 17: Scheme of the oxyfuel cement plant [23]

4.1.5 Chilled ammonia process (CAP)

The Chilled Ammonia Process (CAP) is a type of amine-based scrubbing process that is divided into three main sections:

- Flue gas cooling,
- CO_2 capture,
- Ammonia slip abatement.

In this case, the explanation is about the chemical properties. In the flue gas cooling section, a direct contact cooler (DCC) is used to cool the flue gas and perform ammonia-based desulfurization. The ammonia solution can control multiple pollutants at once. The cooled flue gases are then sent to the absorber, where the ammonia solution reduces the concentration of CO_2. The solution is regenerated in the CO_2 desorbed by heating it with steam to around 120-130°C. The pure CO_2 leaves the column under a pressure of up to 20 bar. The decarbonized flue gases are sent to the ammonia control section, where the ammonia slip is reduced by cooled water before further conditioning by compression or liquefaction.

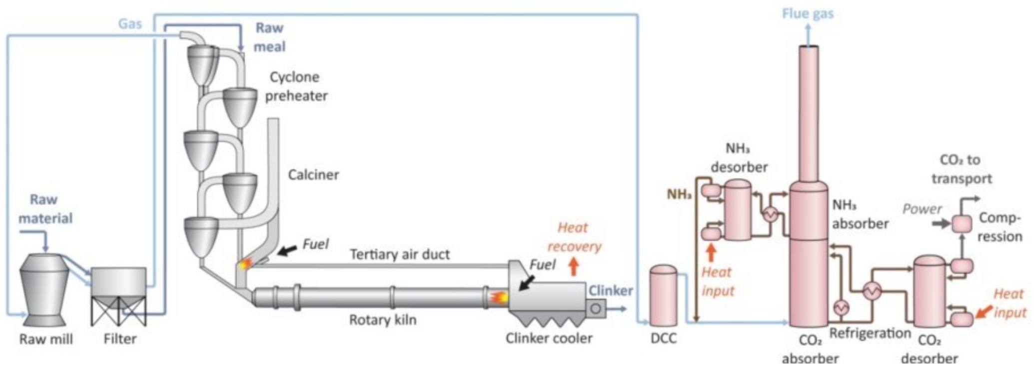


Figure 18: Chilled Ammonia Process (CAP) layout [23]

4.1.6 Membrane-assisted CO_2 liquefaction (MAL)

The membrane-assisted CO_2 liquefaction (MAL) process combines polymeric membrane technology with a CO_2 liquefaction process. This involves using the membranes to separate CO_2 from other gases, resulting in a moderately pure CO_2 product. This product is then sent to a liquefaction process, where the CO_2 is turned into liquid and impurities are removed, resulting in a high-purity CO_2 product.

The flue gas is cooled and compressed before it enters the membrane module. Pressure is generated by both gas compression and vacuum pumps. The need for SOx removal depends on the membrane material, and in CEMCAP, it is assumed that scrubbing with NaOH in the DCC removes SOx. This is a post-combustion technology that requires only power as an input, without any integration or feedback to the cement plant [26].

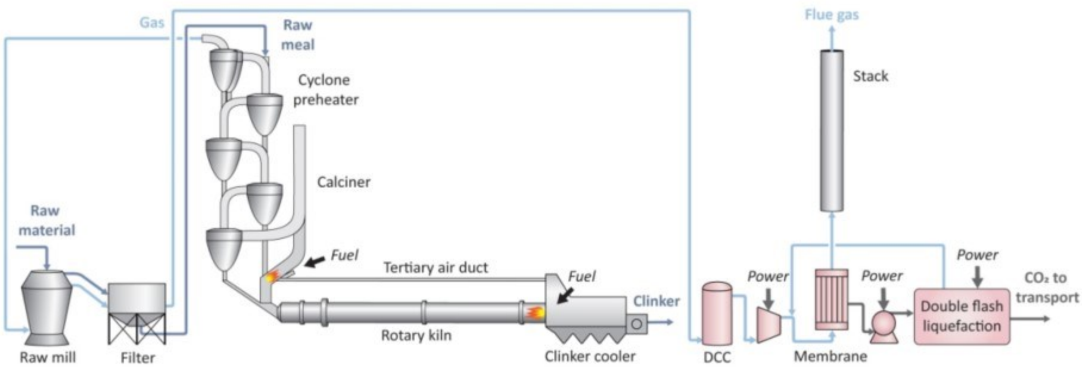


Figure 19: MAL Simplified process scheme for membrane-assisted CO2 liquefaction[23].

4.2 Technical Analysis of Technologies

Based on the information provided and regarding the technologies observed, CEMCAP has created a comparative table that outlines various aspects of each technology.

Capture Technology	MEA	CAP Chilled ammonia process	Membrane assisted CO_2 Liquefaction-MAL	CaL-Calcium looping. CAL	Oxyfuel Capture
Principle of capture of CO_2	Exhaust passes through a cold MEA/water mixture which absorbs CO_2, in a column. CO_2 is released as heat is added to the solution in a subsequent vessel.	Exhaust passes through a cold NH3/water mixture, which absorbs CO_2. CO_2 is released as heat is added to the solution in a subsequent vessel.	A polymeric membrane is used to increase exhaust CO2 concentration. CO2 is separated through condensation after compression and cooling.	CaO particles react with CO_2 to from CaCO3. CO_2 is released in a subsequent vessel through the addition of heat.	Combustion in oxygen mixed with recycled CO_2 (not air) gives a CO_2- rich exhaust.
CO2 purity and capture rate	• Very high CO_2 purity. • Around 90% typical capture rate.	• Very high CO_2 purity. • Around 90% typical capture rate	• High CO2 purity (minor impurities present). • Around 90% typical capture rate.	• CO2 purification needed (CPU). Trade-of between purity, capture rate, and power consumption. • Around 90% typical capture rate. High CO2 purity after purification (CPU) based on very high CPU inlet initial concentration of CO2, around 80 vol.%. Capture rate typically around 90%.	• High CO2 purity after purification (CPU) based on very high CPU inlet initial concentration of CO2, around 80 vol.%. • Capture rate typically around 90%
Integration	Auxiliary low-pressure steam. Can make use of cement plant waste heat if available.	Auxiliary low-pressure steam required. Can make use of cement plant waste heat if available.	Increase in power consumption, no heat integration.	CaCO3 regeneration requires additional fuel, which also enables low-emission electricity generation.	Fuel demand remains unchanged
Energy demand	Electricity required in the core process and for compression.	Electricity required in core process, for chilling and compression.	Electricity required for flue gas compression, vacuum pumps, and refrigeration and compression in the liquefaction system	Increased power consumption due to air separation and CPU partly supplied from heat recovery system.	Increased power consumption due to air separation and CPU, partly supplied from waste heat recovery system

Figure 20: Characteristics of the different capture technologies investigated in CEMCAP [26]

According CEMCAP the techno-economic comparison should be present these points:

- Specific primary energy consumption for CO_2 avoided (SPECCA)
- Cost of Clinker
- Cost of Cement
- Cost of CO_2 avoided [22].

Figure 2 shows that the most significant contributions to the SPECCA vary depending on the technology used. In the MEA process, the primary energy consumption for steam production contributes the most to the added equivalent primary energy consumption and the reduction in equivalent CO_2 avoided. In the oxyfuel process, the added equivalent primary energy consumption and reduction in equivalent CO_2 avoided are primarily due to increased electric power consumption, with the CPU being the most significant power consumption. For the chilled ammonia process, steam consumption is responsible for the most considerable portion of primary energy consumption and CO_2 reduction, while electric power consumption is responsible for the rest. In the membrane-assisted CO_2 liquefaction process, electric power consumption is the only significant factor contributing to added equivalent primary energy consumption and CO_2 reduction, primarily due to fan, pump, and compressor work. In the calcium looping processes, coal, electric power, and electric power generation are crucial factors in the final SPECCA value. The tail-end technology benefits from significant electric power generation, which covers a portion of the cement plant's and CO_2 capture process's demand and contributes to reduced primary energy consumption and CO_2 emissions.

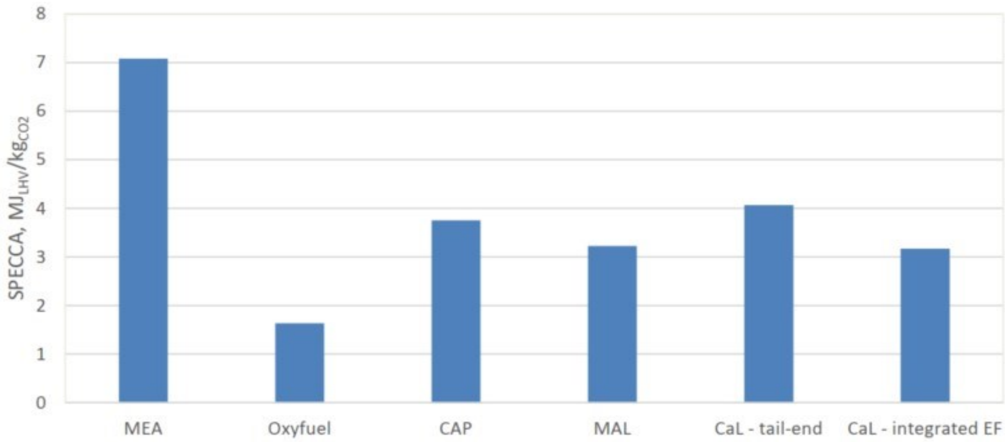


Figure 21: specific primary energy consumption for CO2 avoided (SPECCA) [27]

4.3 Scenario definition

4.3.1 Limitation

One of the primary limitations encountered during this research project was restricted access to financial information relating to the cement industry. While a wealth of technical data is available, financial information is considerably scarce. Some of the available economic data are expressed in units not conducive to accurate cost calculations, which presents an additional challenge. Furthermore, most of the available economic information about past projects dates back more than five years, which hampers the ability to obtain up-to-date information. Considering these limitations, conducting a comprehensive analysis of the industry's economic performance has proven challenging.

The research will focus only on applying the TCO method to the cement industry, and the results cannot be generalized to other industries.
The research will not consider the social impact of implementing sustainable technologies for the cement industry.

4.3.2 Definition

The plant's size is determined to enable the estimation of production capacity, utility consumption, and fixed operating costs.

As Clinker makes up 90% of the components of cement, cement plants typically use it as a reference point in their production calculations. This is because Clinker can be easily compared against cement production as a factor, which provides a more accurate measure of a plant's performance. Chapter two of the document explains this concept in detail. A Clinker is the main component of cement because it provides the binding properties necessary for the mixture to harden and set.
Cement manufacturing involves grinding and blending different raw materials before they are heated in a kiln to produce Clinker. As clinker production is a crucial factor in cement manufacturing, cement plants must track and optimize their production to ensure efficient and sustainable operations. By referencing Clinker in their calculations, cement plants can better understand their production performance and make informed decisions to improve their efficiency and sustainability.

The Best Available Technique (BAT) standard specified in the European BREF-Document for cement manufacturing is adopted as the basis for the benchmark scenario. This standard represents the most advanced and efficient technology available for the cement manufacturing process. This plant, which employs a dry kiln process, includes a five-stage cyclone preheater, a calciner (also known as a pre calciner) with a tertiary duct, a rotary kiln, and a grate cooler. The five-stage cyclone preheater improves heat transfer efficiency by utilizing the exhaust gas from the kiln to preheat the raw material before it enters the kiln. The calciner further enhances fuel efficiency by utilizing the exhaust gas to preheat and partially combust the raw material before it enters the kiln. The resulting combustion gas and material mixture then enters the rotary kiln for complete combustion, where temperatures reach up to 1450°C Finally, ambient air cools the clinker product in a grate cooler. The benchmark scenario and its process model, developed by VDZ, are widely used as a reference in the ECRA project to evaluate the efficiency and sustainability of various cement manufacturing processes [26,27].

The CEMCAP reference [32] shows the following data:

Parameter	Value
Production capacity	1Mtclk/(3000tclk/d)
Cement production	1.36 Mt Cement/y
Clinker/cement factor	0.737
Raw meal/Clinker factor	1.6
Specific CO2 emissions	850 $kgCO_2$/tclk
Specific total electricity	97 kWh/t Cement

Figure 27: Production characteristics of a BAT cement kiln. [27]

According to the BAT regulations, standards and technical criteria are established for the cement production sector in Europe. In this sense, it has been found that there is a tendency for cement plants in Europe to conform to a standardized size.

In the present study, a detailed review of the available reference information has been carried out in order to obtain a completer and more accurate picture, consequently, the study presents similar characteristics in the following table. This case study possesses the following characteristics:

Description	Info per Year	Units Year
Production days	330	days/year
Clinker production	0.96	Mt_{clk}/year
Clinker/cement factor	0.74	Clinker/cement
Cement production	1.30	Mt_{Cem}/year
Emision CO_2	850	kgCO2/tclk

Table 3. Characteristics of the selected cement factory.

Considering energy consumption and financial expenses, oxyfuel technology has been chosen as the most cost-effective approach for decreasing CO_2 emissions. The primary determinants contributing to this outcome are the initial capital expenditures (CAPEX) and ongoing operational costs (OPEX). Additionally, implementing this technology will likely have a more negligible impact on change management since it does not require significant modifications to existing manufacturing processes. This technology can be utilized for new constructions, and in the case of retrofitting, it can be integrated if necessary.

4.3.3 Exclusion

Significant exclusions are:

CO2 emission taxes: This means that any taxes or fees related to the emission of carbon dioxide (CO2) are not included in the calculation or consideration of a particular situation. Excluding CO2 taxes is deemed necessary due to their inherent variability across different countries, regions, and/or manufacturing plant locations. The imposition of CO2 taxes is influenced mainly by the local regulatory and legislative frameworks, which differ significantly from one jurisdiction to another.

Transport and logistics costs: These refer to the expenses related to moving goods or people from one place to another, such as shipping fees, transportation costs, and warehousing fees.

The exclusion of transport and logistics costs is necessary for establishing a fair and equitable framework for assessing the actual cost of manufacturing activities. This is because these costs are highly dependent on various factors, including the manufacturing plant's location, the distance to the final customer, and the specific mode of transportation used. These costs can vary significantly from one manufacturing plant to another, even within the same industry or product category.

Another major factor that influences transport and logistics costs is the location of the final customer. Customers in remote or rural areas may incur higher transportation costs as they are further from major distribution centers and transportation hubs.

Additives in the cement process, the exclusion of this value is justified by its lack of consideration in the relevant benchmarking studies. According to the available evidence and research, this value has not been identified as a critical factor significantly affecting the actual cost of manufacturing activities.

With these exclusions, a standard and equitable reference is established for evaluating and comparing the cost of the product, where there is a focus on the most relevant costs of the process, with which a more accurate and efficient framework can be created.

4.3.4 Details of Oxyfuel process

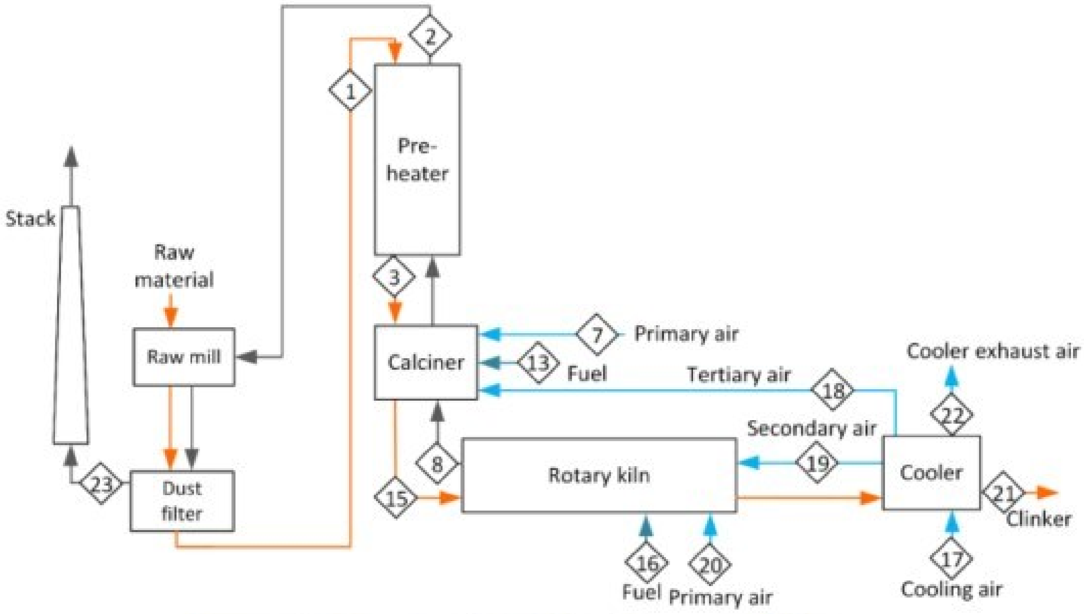
The oxidizer gas stream, created by mixing oxygen from the ASU with CO2-rich flue gas, produces Clinker. The gas is first sent to the clinker cooler to be preheated while cooling the Clinker. Then, some of the preheated air is directed to the rotary kiln main burner and calciner, while the rest is used to preheat air for the raw mill before being recycled back to the clinker cooler. The resulting flue gas has a high concentration of CO2 due to combustion in the main burner and calciner, mixed with gaseous reaction products from the calcination process [27]

After leaving the preheater, the hot flue gases are used to recover heat in a two-stage heat exchanger with hot oil as an intermediate working fluid. The slightly cooled flue gas then goes through a filter for dedusting before water is removed in a condenser. Some the flue gas is recycled and mixed with oxygen, while the rest is conditioned before transport and storage [27].

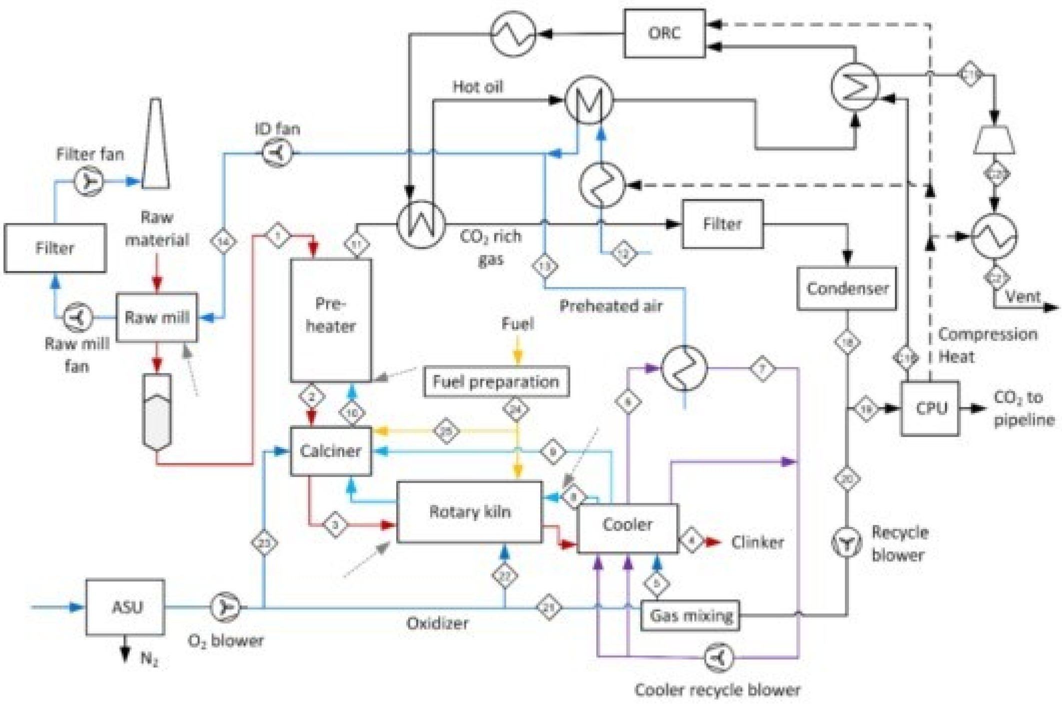
The CPU unit is designed for pipeline transport, compressing CO2 to 110 bar and using molecular sieves for drying. The CO2 is then cooled and liquefied in a multi-stream heat exchanger. Excess heat from the CPU is utilized for electricity generation. The CO2 is compressed to 6.5 bar for ship transport and subcooled to -52°C using external refrigeration. The CPU design for ship transport includes a second liquid-vapor separation stage at the target pressure [27].

The diagram displays a comparison of the process flow and equipment needed to implement oxyfuel technology oxyfuel, Significant variations exist between a standard reference cement plant and key process units within an oxyfuel cement kiln. The primary units that necessitate alteration, substitution, or inclusion are as follows:

- Clinker cooler, with cooler gas recirculation
- Exhaust gas recirculation system
- Gas-gas heat exchangers
- Condenser
- ASU- air separation unit
- Oxygen blower
- CPU- co_2 purification unit
- Rotary kiln main burner for oxyfuel combustion
- Waste heat recovery system (orc)
- Particle removal units upstream of the orc and in the cooler recycle loop



Graphic 1: : Process flowsheet of the reference cement kiln [27]



Graphic 2 Process flowsheet oxyfuel process [27]

5 TCO METHOD

The Total Cost of Ownership (TCO) is a method used to calculate the total cost of acquiring and using a product or service over its lifetime. This method considers all costs associated with the product or service, including the initial purchase price and operational costs such as maintenance.

One of the pioneers in the TCO approach is Cavinato [28], who emphasized the importance of determining the real cost of a product along the supply chain. This involves identifying and evaluating all the costs incurred in the process of acquiring and using a product, including transportation, storage, and handling costs, as well as other indirect costs that can impact the overall supply chain efficiency.

“Humphries and McCaleb proposal is a simplification of Ellram’s and Degraeve’s analysis. Their scope is to identify the most relevant supply costs and evaluate their entity over a certain time horizon through net present value (NPV). See Humphries, McCaleb 2004”. [29] (p 3),[30]

Ellram expanded on this concept by identifying the most relevant costs associated with acquiring and using a product, such as the cost of components and materials, capital equipment, maintenance and services, and supply chain optimization. She also emphasized the need for TCO to be evaluated in an expanded way that takes into account plant operating margins and costs that have an impact on the process. [31]

Although TCO has numerous advantages, it also poses certain limitations and obstacles. One such challenge is the absence of standardization, and another is the requirement for adequate training and expertise to apply the approach effectively. To overcome these barriers, Ellram proposes subdividing TCO into four categories, namely components and materials, capital equipment, maintenance, and services. This approach facilitates the involvement of various departments and stakeholders within the organization [5,32].

In summary, by considering all of these costs, the TCO method provides a more accurate picture of the actual cost of a product or service, allowing organizations to make informed decisions about their procurement choices. Organizations often use TCO to compare the costs of different products or services and evaluate the long-term cost implications of a decision.

In this particular case of study, the TCO model is valuable in understanding the costs associated with cement production and identifying cost categories with the greatest impact on the overall process cost. This model can provide a techno-economic knowledge base for understanding the costs of investments in the cement industry and the impact of external factors outside the control of cement companies.

Moreover, the TCO model provides cost information on technologies that the cement industry can adopt to reduce greenhouse gas emissions. Linking these technologies to the total cost of production allows researchers and or stakeholders to identify the factors that most affect the cost of acquiring such technologies. This understanding can facilitate the calculation of CO_2 emission reductions.

6 COST COMPONENTS

6.1 Economic analysis of technologies

The figure below illustrates the breakdown of clinker cost and CO_2 avoidance cost into crucial cost factors. Implementing CO_2 capture technologies in a cement plant under base case conditions increases the cost of Clinker and cement by 49-92%.

The oxyfuel technology has the lowest cost of Clinker among the CO_2 capture technologies due to lower variable operating and capital costs.

The absorption-based technologies MEA and CAP and both CaL technologies have similar costs ranging from 105-110 €/tclk.

The CaL tail-end technology generates significant electricity, covering the electricity demand of the CO_2 capture process and part of the cement plant's demand. This results in a lower electricity cost per ton of Clinker than the reference cement plant.

The MAL technology has the highest cost of Clinker in the base case, with capital costs being the most prominent individual cost factor. CO_2 avoidance cost is defined as the difference in clinker cost between the reference plant and the plant with CO_2 capture, divided by the equivalent specific avoided CO_2 emissions. Oxyfuel has the lowest CO_2 avoidance cost, with CaL technologies having relatively low costs, especially the tail-end configuration.

	Ref. Cement Plant.	MEA	Oxyfuel	CAP	MAL	CaL Tail End
SPECCA ($MJ_{LHV}/kgCO_2$)	N/A	7.08	1.63	3.75	3.22	4.07
Cost of Clinker (€/t_{clk})	62.51	107.4	93.0	104.9	120.0	105.8
Cost of Cement (€/t_{cement})	46.01	79.0	68.4	77.1	88.2	77.8
Cost of CO2 avoided (€/t_{CO2})	N/A	80.2	42.4	66.2	83.5	52.4

Figure 22: SPECCA and economic KPIs. [26]

Based on the graph below, which presents the breakdown of Clinker costs for the reference cement plant and various CO_2 capture technologies, the following observations can be made:

Capex: The capital expenditure per ton of tclk is lower for Reference plant at 20.8€/t_{clk} and MEA at 28.5€/t_{clk}, and higher for Cal tie end at 43.0€/t_{clk}, followed by MAL at 46.7€/t_{clk} and CAP at 36.5€/t_{clk} Oxy has a Capex cost of 35.1€/t_{clk}, which is in the intermediate range of technologies.

Fixed cost: The fixed cost per ton of tclk is lower for Reference plant at 18.3€/t_{clk} and MEA at 23.9€/t_{clk}, and higher for MAL at 32.2€/t_{clk} and CAP at 27.4€/t_{clk} Oxy has a fixed cost of 25.4€/t_{clk}, which is in the intermediate range of technologies.

Variable cost: The variable cost per ton of tclk is higher for MEA at 6.8€/t_{clk}, followed by Electricity at 2.4€/t_{clk} and Oxy at 2.7€/t_{clk} The variable costs of Cal tie end, Cem. Plant, and MAL are quite low, all below 2€/t_{clk}.

Raw material: The cost of raw material per ton of tclk is quite similar for all technologies, ranging from 4.9€/t_{clk} for MAL to 5.4€/t_{clk} all other technologies, with Cal tie end having the highest cost. Oxy has a raw material cost of 5.3€/t_{clk}, which is in the intermediate range of technologies.

Coal: The cost of coal per ton of clinker is higher for Cal tie end at 21.2€/t_{clk}, followed by MAL at 9.2€/t_{clk} and CAP at 8.9€/t_{clk}, and lower for Oxy and reference plant, both at 9.0€/t_{clk}.

Electricity: The cost of electricity per ton of tclk is higher for MAL at 24.2€/t_{clk}, followed by CAP at 16.3€/t_{clk}, MEA at 14.2/€/t_{clk}, and Oxy at 12.2€/t_{clk}. The cost of electricity for Cal tie end is quite low at 3.6€/t_{clk}. Reference plant does not consume electricity.

Steam: The cost of steam per ton of tclk applies only to MEA at 19.7€/t_{clk} and CAP at 11.8€/t_{clk}.

Total: The total cost per ton of tclk is Oxy at 93.0€/t_{clk}, and Reference plant at 62.6€/$t_{clk;}$ they are the cheaper cost in comparison between all technologies.

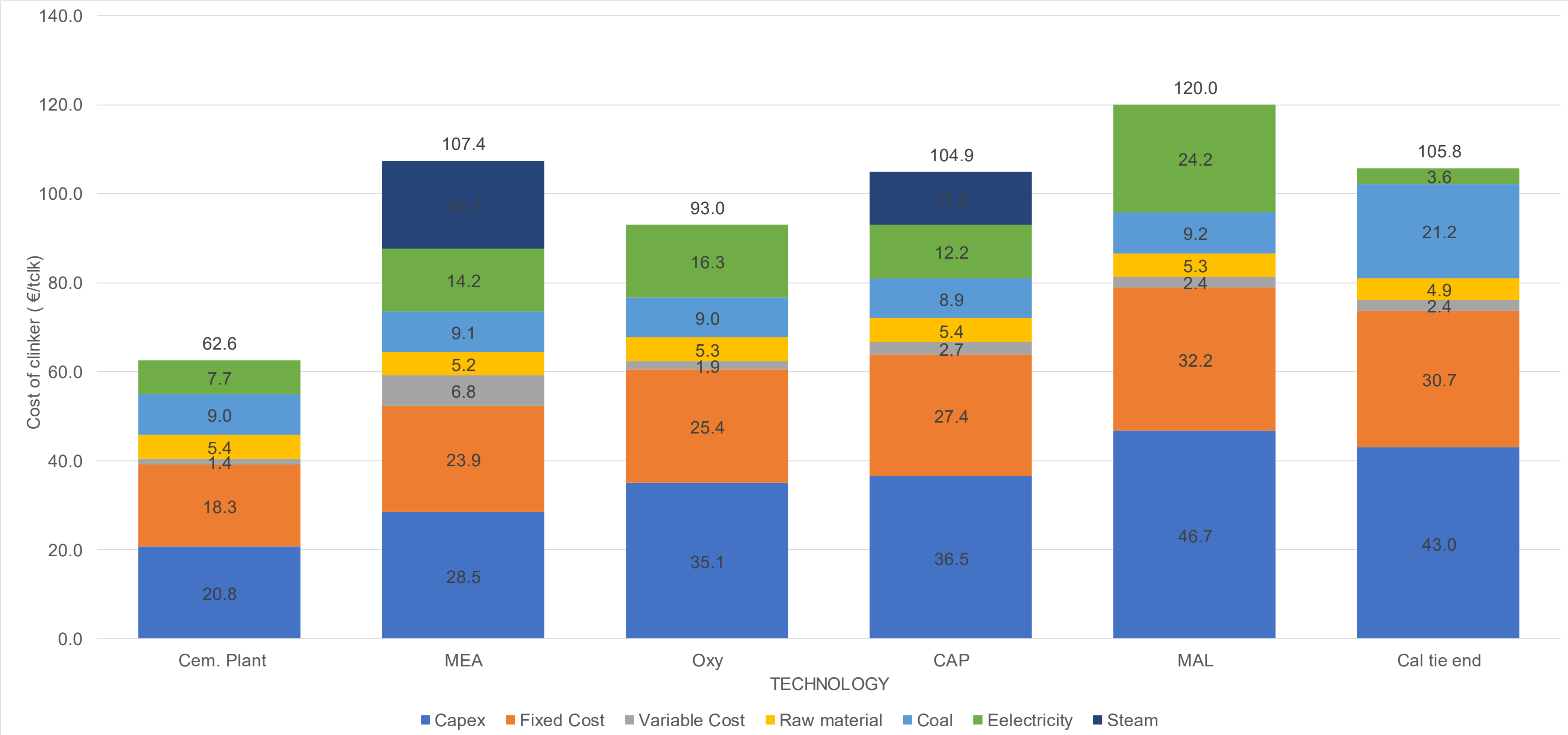


Figure 23: Break-down of cost of Clinker for the reference cement plant and the base case of all the investigated CO_2 capture technologies [27]

Considering the additional studies referenced in the literature review, a comparative chart has been constructed to provide a more comprehensive understanding of the expenses associated with cement manufacturing.

This will equip us with additional resources for choosing a technology to execute the TCO [24,33–36]; follow the table 1.

Comparative TCO calculation of different technologies based on reference information.

The results in the table below reveal that the highest cost of clinker is linked to the Gardarsdottir method for CAL Tail End in 2019, with a cost of €119.6/tclk, followed by the Gardarsdottir method for Post-combustion Amine in 2021, with a cost of €107.4/tclk. Conversely, the lowest cost of clinker is linked to the IEA greenhouse method for Oxyfuel Combustion in 2008, with a cost of €65.6/tclk, and the LEILAC method for Base Case in 2008, with a cost of €81.7/tclk.

Regarding variable costs, the results indicate that the lowest cost is associated with the LEILAC method for Oxy Combustion in 2021, with a cost of €16.8/tclk, followed by the Gardarsdottir method for Base Case MEA in 2019, with a cost of €23.5/tclk. In contrast, the highest variable cost is linked to the Gardarsdottir method for Base Case CAP in 2019, with a cost of €55/tclk, followed by the Gardarsdottir method for Base Case in 2019, with a cost of €55.8/tclk.

Concerning fixed costs, the lowest cost is associated with the IEA greenhouse method for Base Case in 2008, with a cost of €19.1/tclk, followed by the Zemcero method for PLASMA in 2018, with a cost of €19.6/tclk. In contrast, the highest fixed cost is associated with the Gardarsdottir method for CAL Tail End in 2019, with no specified cost, followed by the LEILAC method for Base Case in 2021, with no specified cost.

Finally, the analysis shows that the lowest CAPEX is linked to the IEA greenhouse method for Oxyfuel Combustion in 2008, with a cost of €29.7/tclk, followed by the Gardarsdottir method for Base Case in 2021, with a cost of €28.5/tclk. In contrast, the highest CAPEX is linked to the LEILAC method for Base Case in 2008, with a cost of €63.1/tclk, followed by the Gardarsdottir method for Post-combustion Amine in 2021, with a cost of €62.6/tclk.

Overall, the results demonstrate that the costs of clinker vary considerably across different methods used in the cement industry. The Gardarsdottir method for CAL Tail End and Post-combustion Amine methods show significantly higher costs compared to the IEA greenhouse method for Oxyfuel Combustion and the LEILAC method for Base Case. It is essential to consider various factors, such as technology type, energy efficiency, and raw material costs, among others, that can impact the cost of clinker in cement production.

From the information presented, it can be understood that the average cost of manufacturing Clinker without CCS is 55€/t and 101.94€/t for CCS. In contrast the lowest costs for Clinker production with CCS is 81.7€/t versus 129.4 being the highest cost.

Oxyfuel combustion technology is the lowest cost associated with one of the capture technologies.

Conventions:

Conventions
Technology without CCS
Technology with CCS

Research \ Tecnology	Zemcero			IEA greenhouse			LEILAC			Gardarsdottir, S.				
Description	**without CCS BY ZemCero 2018**	**ZemCero AMINA 2018**	**ZemCero PLASMA 2018**	**IEA greenhouse Base Case 2008**	**IEA Post conbustion capture 2008**	**IEA Oxyfuel Comb. 2008**	**LEILAC Base Case 2021**	**LEILAC Oxy Combustion 2021**	**LEILAC Amine 2021**	**Gardarsdottir. 2019 Base Case**	**Gardarsdottir. MEA 2019**	**Gardarsdottir. Oxyfuel 2019**	**Gardarsdottir. CAP 2019**	**Gardarsdottir. CAL Tail End 2019**
Variable Cost	13,4	42,5	49	16,8	31	22	39	77	55,8	23,5	55	32,5	41	40,7
Fixed Cost	14,9	19,6	19,1	19,1	35,3	22,8	-	-		18,3	23,9	25,4	27,4	32,2
CAPEX	24,3	39,4	32	29,7	63,1	36,9	-	15	34	20,8	28,5	35,1	36,5	46,7
Cost of clinler €/tClk	**52,6**	**101,5**	**100,1**	**65,6**	**129,4**	**81,7**	**39,0**	**92,0**	**89,8**	**62,6**	**107,4**	**93,0**	**104,9**	**119,6**

Table 1-Cost comparison of Cement production different technologies.

The following table presents the average calculation of the two technologies; additionally, we have determined the minimum and maximum cost to establish which technology with capture corresponds to these ranges.

Description	Average WithOut CCSPlant	Average with CCS	Lowest with CCS	Hights with CCS
Cost of cement (€/tClk)	55,0	101,94	81,7	129,4

Table 2-Resume cost comparison Table 1

6.2 Cost Components

The following costs will be used for this study:

- Variable Cost
- Fixed cost
- Capital expenditure.

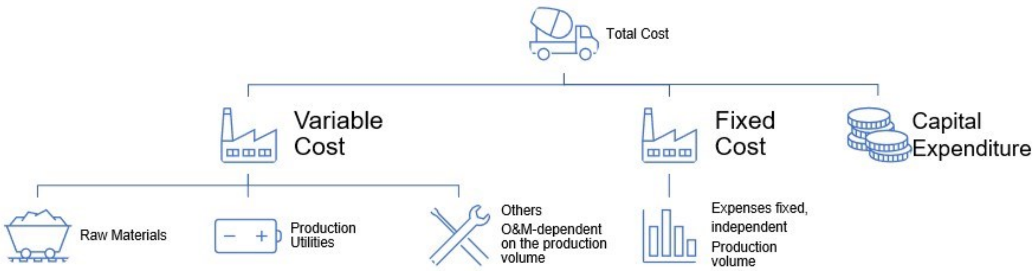


Figure 24: TCO Components[37]

6.2.1 Variable cost

“A variable cost is a corporate expense that changes in proportion to how much a company produces or sells. Variable costs increase or decrease depending on a company's production or sales volume—they rise as production increases and fall as production decreases” **.** [38] Some of these costs are those associated with raw materials, production services, operating expenses.

When a company increases its production or sales, it also incurs additional variable costs, such as direct labor and raw materials. These costs are directly tied to the output level and vary based on the company's production volume. Conversely, variable costs will also decrease when the production or sales volume decreases because there is less need for direct labor and raw materials.

Variable costs play a significant role in calculating a product's contribution margin, which is the difference between the product's sales revenue and variable costs. This metric is used to assess the profitability of a product and determine how much it contributes to covering a company's fixed costs, such as rent, utilities, and equipment [39].

In this research, we have incorporated the primary expenses necessary to function as variable costs. These expenses comprise raw material, which is the mineral utilized for converting into Clinker, utilities such as coal, cooling water for the capture process, and other O&M variable costs that pertain to the specific consumption expenses of the operation. However, these variable costs are stable per unit of product.

For this study the information about [40] variable cost is:

RATIO for VARIABLE COST WITHOUT CCS			
Material description	**Rate**	**Unit**	**Reference**
Raw Meal	1.66	$t_{RawMeal}/t_{clk}$	[40]
Gypsum 99%	0.03	Gym/t_{Cem}	[41]
Electricity	0.13	MWh/t_{clk}	[40]
Coal	3.14	GJ_{LHV}/t_{clk}	Assumption based [40]
RATIO for VARIABLE COST WITH CCS			
Material description	**Rate**	**Unit**	**Reference**
Gypsum 99%	0.03	Gym/tCem	[41]
Electricity	0.28	MWh/tclk	[36]
Coal	3.14	GJ_{LHV}/t_{clk}	[35]
Cooling water	10.00	m^3/t_{clk}	[40]
COST for VARIABLE WITHOUT CCS			
Description	**Unit Cost**	**Unit**	**Reference**
Raw Meal	5.00	€/tRawMeal	[35]
Gypsum 99%	62.72	€/tCem	[42]
Electricity	149.90	€/MWh	[44]
Coal	3.62	$€/GJ_{LHV}$	[35]
Other Variable O&M	1.10	$€/t_{clk}$	[22]
COST for VARIABLE COST WITH CCS			
Description	**Unit Cost**	**Unit**	**Reference**
Gypsum 99%	62.72	€/tcem	[42]
Electricity	149.90	€/MWh	[44]
Coal	3.14	GJ_{LHV}/t_{clk}	[40]
Cooling water	0.39	$€/m^3$	[22]

Table 3: Detail of variable costs.

The table presents the variable cost breakdown for a cement plant without CCS (carbon capture and storage) and with CCS using Oxyfuel technology. The variable costs include procurement, production cost-utilities, and other variable O&M costs.

Regarding procurement, the raw meal is required for Clinker production and is calculated at a rate of 1.66 $t_{RawMeal}/t_{clk}$ for both plants. The unit cost of raw meals is €5.00/$t_{RawMeal}$, resulting in a cost of €8.30/tclk without CCS and €8.30/tclk with CCS.

Under production cost-utilities, electricity is required for the operation of the plant. Without CCS, the rate is 0.1319 MWh/tclk, and the unit cost is €149.90/MWh, resulting in a cost of €19.77/t_{clk}. With CCS, the rate increases to 0.2783 MWh/tclk, costing of €41.72/tclk. Additionally, coal is needed for Clinker production and is calculated at a rate of 3.50 GJ_{LHV}/t_{clk}, with a unit cost of €3.62/GJ_{LHV}, resulting in a cost of €12.66/t_{clk} for both plants. Cooling water is also required for the plant with CCS, with a rate of 10 m^3/t_{clk} and a unit cost of €0.39/m^3, resulting in a cost of €3.90/t_{clk}.

Other variable O&M costs have a unit cost of €1.10/t_{clk} for both plants.
The total variable cost for the plant without CCS is €41.83/t_{clk}, while the plant with CCS has a higher variable cost of €67.68/t_{clk}, primarily due to the increased electricity and cooling water requirements.

6.2.2 Fixed cost

Also known as indirect costs, refer to the expenses incurred by a business that remain unchanged regardless of the quantity of goods, services, or products produced or sold. These expenses are typically recurring and not directly associated with production, such as rent, administrative salaries, insurance, and interest payments. These costs are referred to as indirect as they are not linked to the production of goods or services by a company [39].

Several references were used to calculate the fixed cost, as these references were based on Capex other in Variable Opex. A table was generated to determine the cost values, and an average was calculated for the present study. The exact process was followed for both technologies. It should be noted that fewer references are available for the capture technology, as the data pertains solely to oxyfuel technology.

- **References**

DESCRIPTION	CEMCAP (BASED CAPEX)	CEMENT 2017 EUR COMMISSION	LIME -EUR COMMISSION 2017	EXPERT 2023	IEAGHG 2008	AVERAGE	Units
Maintenance	3%	13%	11%	35%	5%	13%	%
Insurance and tax	2%	6%	6%	5%	1%	4%	%
Labour (adm. Support ant operation)	4%	22%	16%	60%	30%	26%	%

- **Calculation**

DESCRIPTION	CEMCAP	CEMENT 2017 EUR COMMISSION	LIME -EUR COMMISSION 2017	EXPERT 20232	IEAGHG 2008	AVERAGE	Units
Maintenance	6.03	5.44	4.61	14.65	2.09	5.61	€/tclk
Insurance and tax	4.02	2.51	2.51	2.09	0.42	1.67	€/tclk
Labour (adm. Support ant operation)	8.04	9.21	6.70	25.12	12.56	11.05	€/tclk
Total €/tclk	**18.09**	**17.17**	**13.82**	**41.87**	**15.07**	**18.34**	**€/tclk**

Table 4-Calculation Fixed Cost Without CCS.

Maintenance	CEMCAP 2014	GARDARSDOT 2019	IEAGHG 2008	ECRA 2009	AVERAGE	Units
Maintenance	8.30	-	10.80	10.7	9.93	€/tclk
Insurance and tax	6.60	-	5.80	5.8	6.07	€/tclk
Labour (adm. Support ant operation)	10.40	-	6.20	6.25	7.62	€/tclk
Total	**25.30**	**25,30**	**22.80**	**22.75**	**23.62**	**€/tclk**

Table 5-Calculation de Fixed Cost With CCS.

The fixed costs are distributed among three categories: maintenance expenses, insurance and taxes, and labor costs of administrative, support, and cross-functional personnel not directly involved in the operation.

The following table presents the outcomes of the fixed cost components.

Description	Average without CCS	Average with CCS	Units
Maintenance	5.61	9.93	€/tclk
Insurance and tax	1.67	6.07	€/tclk
Labour (adm. Support ant operation)	11.05	7.62	€/tclk
Total	**18.34**	**23.62**	**€/tclk**

Table 6-Fixed cost comparative.

The table shows the breakdown of the fixed cost for a cement industry operation without and with CCS (carbon capture and storage) technologies. The fixed cost components include maintenance, insurance and tax, and labor (administrative support and operation).

Without CCS, maintenance costs account for 13% of the fixed cost, which amounts to 5.61 €/t_{clk} (a ton of Clinker). Insurance and tax represent 4% of the fixed cost, which is equivalent to 1.67 €/t_{clk}. Labor costs, including administrative support and operation, make up the largest share of the fixed cost at 26%, amounting to 11.05 €/t_{clk}.

With CCS, the percentage of fixed cost for maintenance increases to 24%, resulting in a cost of 9.93 €/t_{clk}. Insurance and tax expenses also increase to 14% of the fixed cost, amounting to 6.07 €/t_{clk}. However, the percentage of fixed cost for labor decreases to 18%, resulting in a lower cost of 7.62 €/t_{clk}.

Overall, the total fixed operating cost increases from 18.34 €/t_{clk} without CCS to 23.62 €/t_{clk} with CCS, primarily due to increased maintenance, insurance, and tax costs.

6.2.3 Capital expenditure

Commonly abbreviated as CapEx, it refers to the financial resources that a company allocates toward acquiring and improving assets. These expenses are often used to initiate new investments or ventures. When a company invests in fixed assets, it may involve acquiring a new piece of equipment or building a new factory; several purchases may be classified as CapEx. These include buildings that serve as offices, manufacturing facilities, inventory storage, or for other purposes, equipment, machinery, computers, servers, software, furniture, and vehicles, all of which may be considered CapEx as they serve various operational purposes within the company. Finally, patents may hold long-term value if the company can develop a product based on the idea. [45]

To calculate the CapEx, initial data from references were collected and averaged. The average data was used in the case without CCS, whereas the CEMPCAP reference was used for CCS as it provides the necessary complementary information.

DESCRIPTION	CEMCAP 2014	MEA 2017	CEMZERO 2019	EXPERT 2023	AVERAGE	UNITS
Total Direct Costs (TDC)	149.82	149.00	145.00	149.00	148.21	M€
Indirect costs	14%	14%	45%	45%	29%	*(% of TDC)*
Engineering, Procurement & Construction.(EPC)	20.97	20.86	65.00	67.05	43.66	M€
Subtotal	170.79	169.86	210.00	216.05	191.86	
Owner's costs	7%		5%	5%	6%	*(% of TDC)*
Project Conting.	14%	19%	5%	15%	13%	*(% of TDC)*
Owner's costs	11.96	32.27	10.50	10.80	10.87	M€
Project Conting. Cost	23.91		10.50	32.41	25.42	M€
Total Capital Required	**206.66**	**202.13**	**231.00**	**259.26**	**228.16**	**M€**

Table 7-Calculation CAPEX Without CCS.

DESCRIPTION	CEMCAP 2014	IEA 2008	GARDARSDOTTIR	ECRA 2016	AVERAGE	UNIT
Total Direct Costs (TDC)	73.10	20.00	-	160.50	-	M€
Indirect costs	13.20	-	-	-	-	M€
Process Contingencies	20.90	-	-	-	-	M€
Eng. Proc. Constr. (EPC)		23.00	-	144.50	-	M€
Owner's costs	6.60	2.60	-	15.00	-	M€
Project Conting. Cost	14.10	4.00	-	17.00	-	M€
fees		1.00	-	6.00		M€
Capital Required CCS-Oxyfuel	127.90	50.60	128.00	343.00	**102.17**	M€
Capital Required without CCS	206.66	276.00	204.00	231.00	**228.89**	M€
Total Capital Required with CCS Capture-Oxyfuel	**334.56**	**326.60**	**332.00**	**574.00**	**331.05**	**M€**

Table 8--Calculation CAPEX With CCS.

In the present study we have the following data:

Capital Cost	Without CCS %	Without CCS M€	With CCS %	With CCS M€
TDC		148.21		222.9
EPC	29%	43.66	16.5%	55.2
Owner Cost	6%	10.87	5.5%	18.4
Contingencies	13%	25.42	11.4%	38.1
Total		**228.16**		**334.64**

Table 9-CAPEX selected for analysis.

Based on the data presented in the table, it is evident that the equipment cost exhibits an increase from 148.2M€ to 222.9M€ in the absence and presence of CCS technologies, respectively. Moreover, the EPC cost also shows an upward trend, rising from 43.6 M€ to 55.2 M€, while the Owner cost rises from 10.87 M€ to 18.40 M€, and the contingencies increase from 25.42 M€ to 38.14 M€.

6.2.4 Complementary information

The table contains essential data for Total Cost of Ownership (TCO). The tables include pertinent details such as ratios, interest values, and the per-ton calculation for the Capital Expenditure per ton of Clinker and ton of cement.

Interest rate (i): The interest rate for both cases is the same, which is 5%. This means that the cost of borrowing money is the same for both scenarios [46,46].

The Lifetime of facilities (t): The lifetime of the facilities in both cases is the same, 25 years. This means the facilities will last for the same amount of time, regardless of whether or not CCS is used [22].

Recovery factor: the recovery factor of 0.07 would refer to the percentage of capital expenditure that can be recovered over the lifetime of the facilities. This means that for every €100 spent on the facilities, €7 can be recovered over the project's lifetime [22].

CAPEX per year:
The CAPEX (capital expenditure) per year for the case without CCS is €16.19 million, while the CAPEX per year for the case with CCS is €23.74 million. This means that implementing CCS will increase the yearly capital expenditure by €7.55 million.

CAPEX per ton of Clinker:
The CAPEX per ton of Clinker for the case without CCS is 16.94€/t_{clk}, while the CAPEX per ton of Clinker for the case with CCS is 24.84 €/t_{clk}. This means implementing CCS will increase the cost per ton of Clinker by 7.90 €/t_{clk}.

CAPEX per ton of cement:
The CAPEX per ton of cement for the case without CCS is 12.48 €/t_{cem}, while the CAPEX per ton of cement for the case with CCS is 18.31€/t_{cem}. This means implementing CCS will increase the cost per ton of cement by 5.83€/t_{cem}.

Description	Without CCS Value	Unit	With CCS Value2	Units2
Interest rate (i)	5%	%	5%	%
Lifetime of facilities (t)	25	year	25	year
Recovery factor	0.07		0.07	
CAPEX per YEAR	16.19	M€	23.74	M€
CAPEX per ton Clink	**16.94**	**€/tclk**	**24.84**	**€/tclk**
CAPEX per ton Cement	12.48	€/tcem	18.31	€/tcem

Table 10-Complementary information.

7 THE RESULTS

The research sought to compare the total cost of ownership (TCO) of two scenarios: a new cement plant without carbon capture technology and a new cement plant with carbon capture using Oxyfuel technology. The TCO was calculated based on several critical factors, including utility consumption, fixed operating expenses, and capital investment costs.

Detailed data were gathered and analyzed to compare the TCO of these two scenarios. This included information on the rates and costs of raw materials procurement, electricity consumption, coal usage, cooling water requirements, and other variable operation and maintenance costs.

This analysis provides valuable insights into the financial implications of implementing carbon capture technology in the cement industry. Comparing the TCO of a greenfield plant with and without carbon capture technology makes it possible to determine the potential cost savings or additional expenses associated with implementing such technology. This information is highly relevant for cement industry stakeholders seeking to make informed decisions about investments in carbon capture and other sustainability initiatives.

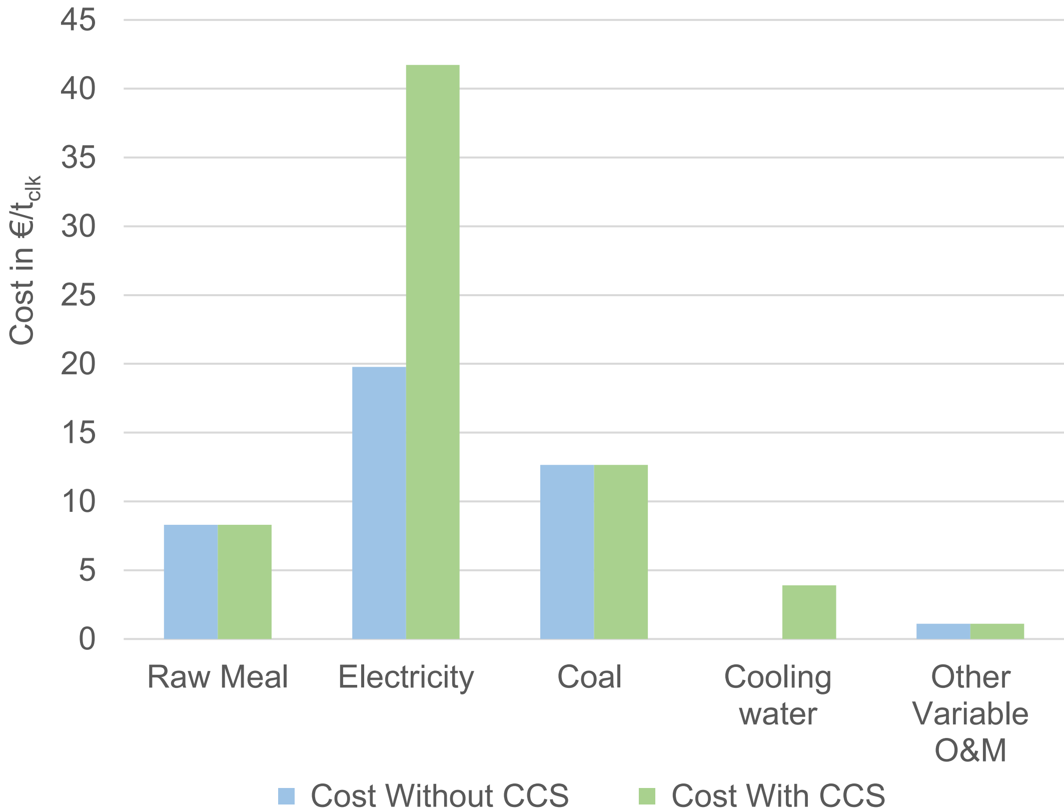
7.1 Variable cost

It should be noted that the percentages shown here are calculated according to the variable cost for each technology, which represents the exact cost as the raw meal and coal, but in percentage according to the Total presents a decrease in percentage, while for electricity and cold water even with this represents an increase in the consumption of these facilities, which is the same in the raw meal and coal, but in percentage according to the Total presents a decrease in percentage.

The graph illustrates that both scenarios keep raw meal, fuel consumption, and other O&M expenses constant. However, electricity accounts for 47% of the total value in the scenario without carbon capture, whereas in the scenario with CCS, it amounts to 61%. Regarding costs, electricity consumption in the capture scenario is approximately double that of the non-capture scenario. Additionally, the capture scenario incurs a minor rise in cold water usage during the process, as it is unnecessary for the first scenario. Cold water consumption in the capture scenario represents 6% of the total variable cost.

Description	Without CCS	Units	With CCS	Units2
Raw Meal	8.30	€/tclk	8.30	€/tclk
Electricity	19.77	€/tclk	41.72	€/tclk
Coal	12.66	€/tclk	12.66	€/tclk
Cooling water			3.90	€/tclk
Other Variable O&M	1.10	€/tclk	1.10	€/tclk
Total	**41.83**	**€/tclk**	**67.68**	**€/tclk**

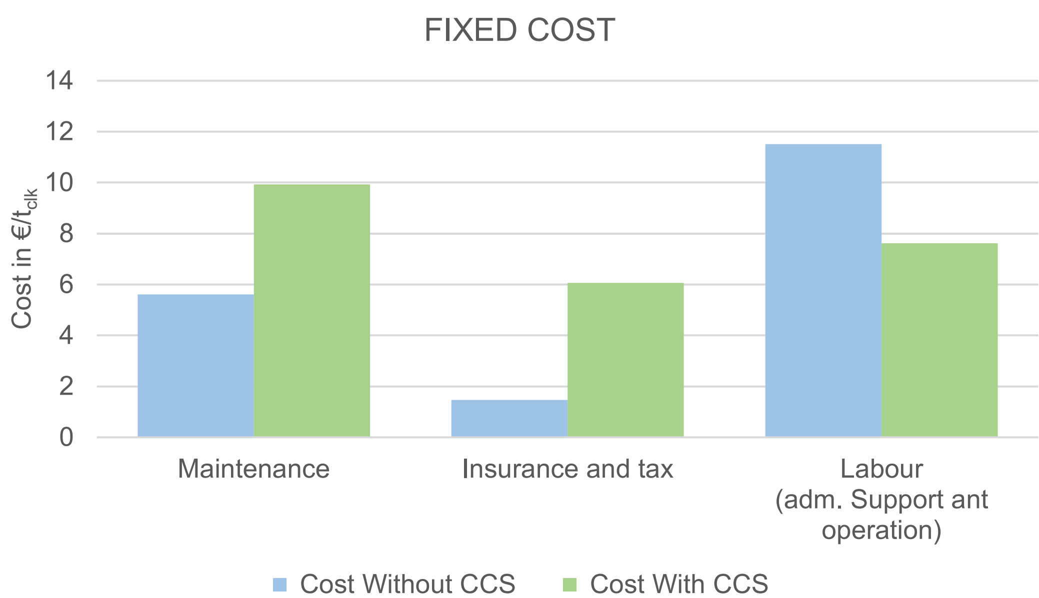
Table 11. Comparative variable cost.



Graphic 3: Comparative variable cost.

7.2 Fixed cost

In the graph, it can be observed that fixed costs in the maintenance section increased from 30% to 42%. This is due to an increase in the number of pieces of equipment that require maintenance. Insurance and taxes also increased from 8% to 18%, related to the increase in equipment. Additionally, as the technology is still in development, there are no risk references, resulting in higher insurance costs. In the labor section, there is a decrease of 27% as the support staff remains unchanged despite the technological shift.



Graphic 4.Comparative Fixed Cost.

7.3 Capital expenditure

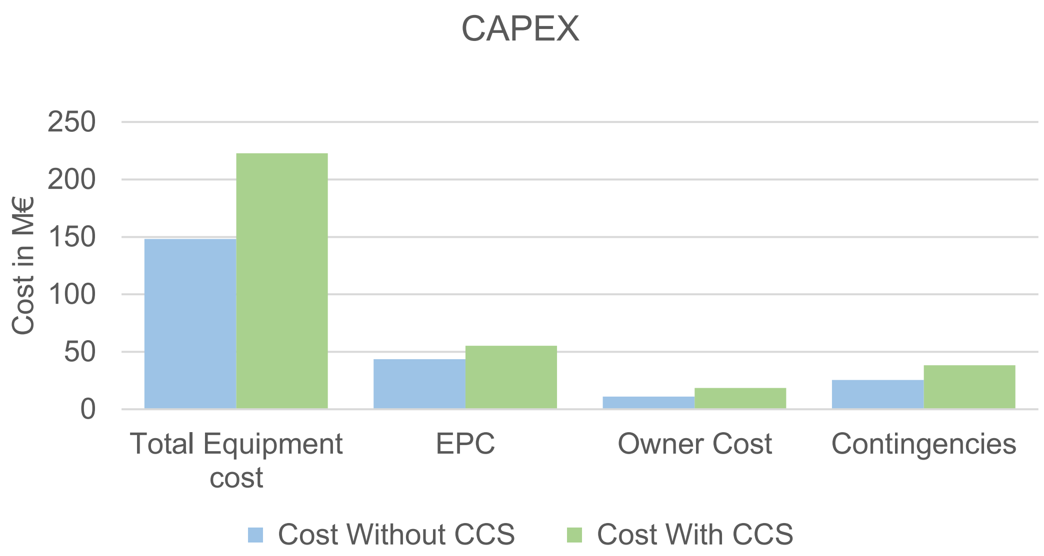
Upon analyzing the graph, it is evident that the most substantial variation in capital expenditure is observed in the total equipment cost. *Despite being calculated based on the respective technology's* CAPEX, they fall within a similar range, at 65% and 67%. However, this 2% in cost term corresponds to the plant without carbon capture, which cost is 148.21 M€, while for the plant with carbon capture, the cost is 222.90 M€. This represents an increase of approximately 50%.

The EPC (Engineering, Procurement, and Construction) cost is the second-largest cost for both plants. The EPC cost for the plant without carbon capture is 43.66 M€, while for the plant with carbon capture, the cost is 55.20 M€.

The Owner Cost and Contingencies make up the remaining costs.

The Owner Cost and Contingencies make up the remaining costs. The cost for Owner Cost for the plant without carbon capture is 10.87 M€, and for the plant with carbon capture, it is 18.40 M€. The Contingencies cost for the plant without carbon capture is 25.42 M€, and for the plant with carbon capture, it is 38.14 M€.

Overall, the graph shows that the cost of ownership for a greenfield cement plant with carbon capture using Oxyfuel technology is higher than that of a plant without carbon capture.



Graphic 5-Capital Expenditure-CAPEX.

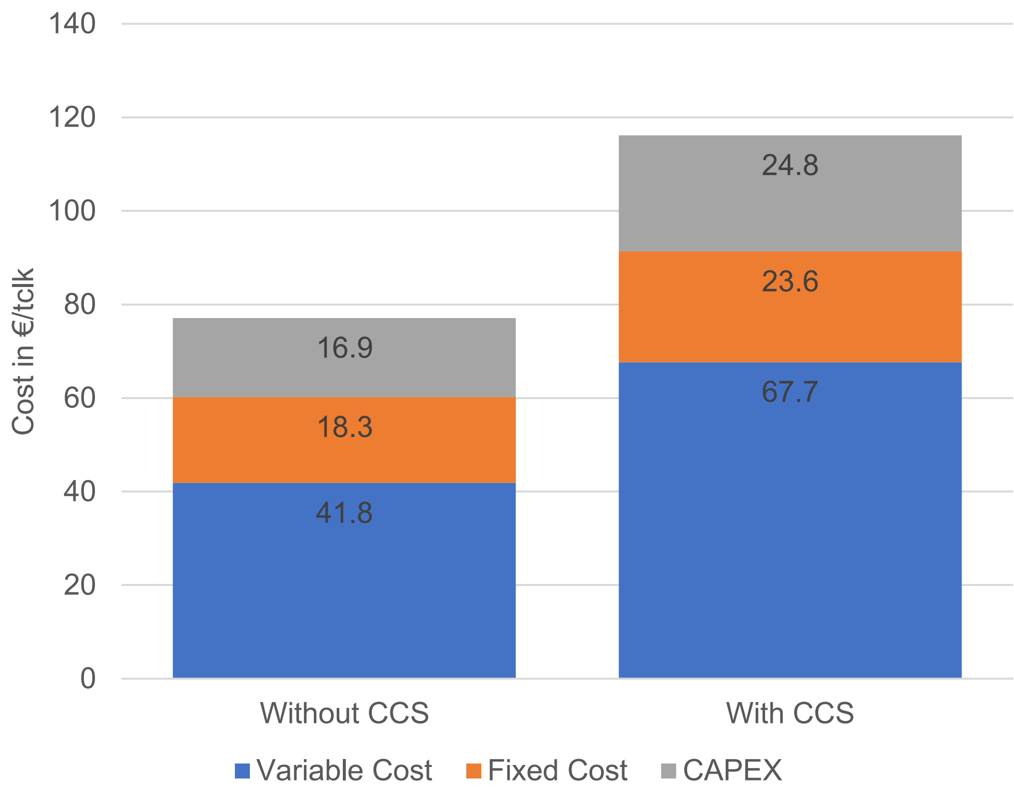
7.4 Total Cost Ownership (TCO)

As can see from the graph provided, there is a significant difference in cost between the two scenarios.

TCO Calculation	Without CCS		With CCS	
Item	Without CCS	Unit	With CCS	Units
Variable Cost	41.83	€/tclk	67.68	€/tclk
Fixed Cost	18.34	€/tclk	23.62	€/tclk
CAPEX	16.94	€/tclk	24.84	€/tclk
TCO of Clinker	**77.11**	**€/tclk**	**116.14**	**€/tclk**
TCO Cement	**56.83**	**€/tcem**	**85.60**	**€/tcem**

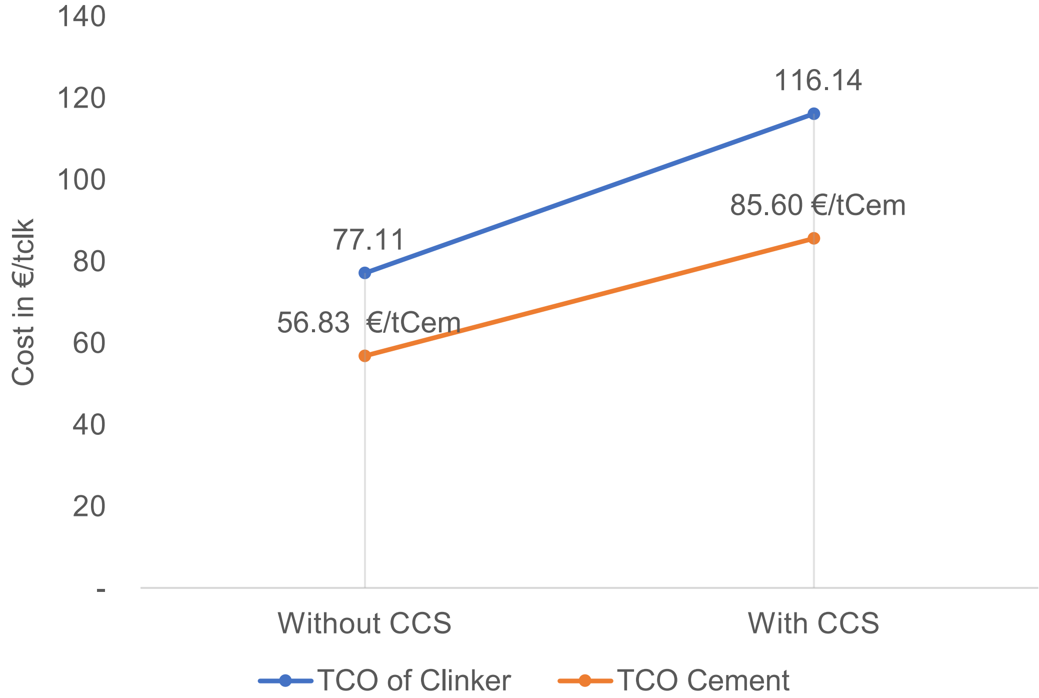
Table 12-TCO for the Cement industry without CCS and with CCS.

The TCO discriminated: The total cost of ownership (TCO) is higher with CCS than without CCS. Clinker's variable cost per ton of Clinker is 67.68 €/t_{clk} with CCS compared to 41.83 €/t_{clk} without CCS. Clinker's fixed cost per ton is 23.62 €/t_{clk} with CCS compared to 23.62 €/t_{clk} without CCS. The CAPEX per ton of Clinker is slightly higher with CCS 24.84€/t_{clk} compared to without CCS 16.94 €/t_{clk}.



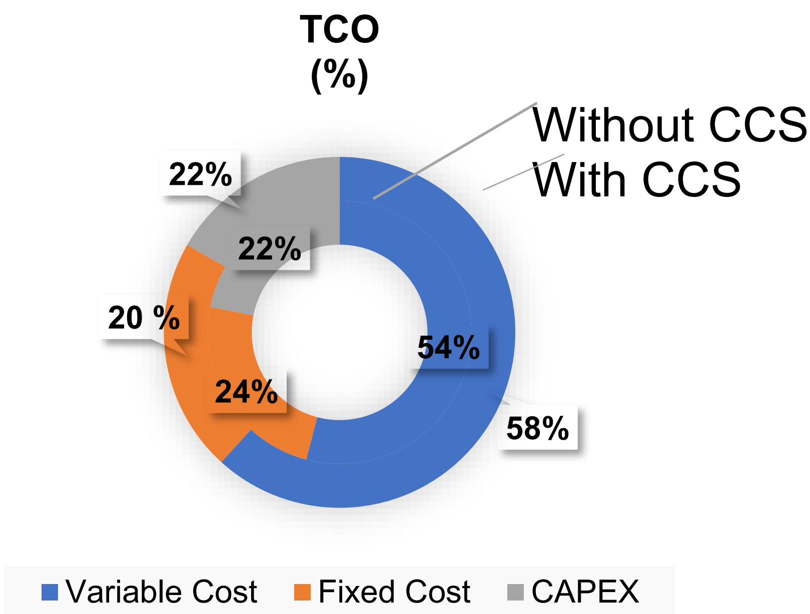
Graphic 6-TCO for technology Without CCS & Oxyfuel capture technology.

The total cost of ownership (TCO) is higher with CCS than without CCS. The TCO per ton of Clinker is 109.61 €/t_{clk} with CCS compared to 77.36 €/t_{clk} without CCS. The TCO per ton of cement is 80.78 €/t_{cement} with CCS compared to 57.01 €/t_{cement} without CCS.



Graphic 7- TCO -Without cost discrimination.

TCO discrimination read as a percent can claim to show us: The variable cost makes up a higher percentage of the TCO with CCS 62% compared to those without CCS 54%. The fixed cost makes up a lower percentage of the TCO with CCS 22% compared to without CCS 24%. The CAPEX makes up a lower percentage of the TCO with CCS 17% compared to without CCS 22%. Overall, the results suggest that implementing CCS will increase the variable cost of production while reducing the fixed cost and CAPEX.



Graphic 8-Comparative TCO in %, without & with CCS technology.

The analysis of Total Cost of Ownership (TCO) revealed that the implementing of capture technology in the cement industry leads to a notable increase in product cost of 28.7 €/t_{Cem} compared to the cost without it. This hike is primarily due to the expenses incurred in implementing Oxyfuel technology. According to the data, the variable cost of cement production without CCS technology is 41.83 €/t_{clk}. In comparison the cost with CCS technology is 67.68 €/t_{clk}, resulting in a significant increase of 162% in the cost of capture technology compared to the cost without CCS.

Notably that the difference in cost between utilizing capture technology and not using it represents a substantial increase of 42% in the cost per tonne of cement compared to the current technology that does not employ capture. Therefore, it is vital to align long-term objectives and strategies with the production requirements of the cement industry to ensure the successful implementation of CO2 capture technology. This will require a detailed plan, stakeholder engagement, and communication of the benefits of reduced carbon emissions, improved sustainability, and potential cost savings.

Despite the substantial increase in cost, the integration of capture technology is essential for reducing carbon emissions and mitigating the environmental impact of the cement manufacturing process. However, it is crucial to consider the associated costs before implementing the technology.

The other hand understanding the Cost of Avoided Carbon (CAC) is an essential aspect of evaluating the cost-effectiveness of various strategies for reducing carbon emissions. The CAC is the cost of eliminating or avoiding the release of one ton of CO2 into the atmosphere. By calculating the CAC for different emission reduction strategies, decision-makers can make informed choices based on their cost-effectiveness. For instance, a company can compare the CAC of investing in renewable energy sources such as wind and solar power against the CAC of investing in carbon capture and storage (CCS) technologies.

The significance of calculating the CAC lies in the fact that it offers a standardized and uniform way to compare the relative costs of various carbon reduction strategies. With the help of the CAC, decision-makers can determine the most cost-effective approach to reducing carbon emissions. For example, a company that wants to reduce its CO2 emissions by one tonne

The Oxyfuel Carbon Capture and Storage (CCS) technology has a CAC of 42 euros per tonne of CO2 (tCO2), which means the cost of capturing and storing one tonne of CO2 emissions using that technology is 51 euros.

Cost CO2 Avoided	Cost	Units
CAC	51.02	€/tCO_2

Table 13: CAC -Cost of Avoided Carbon of CO2. Own elaboration

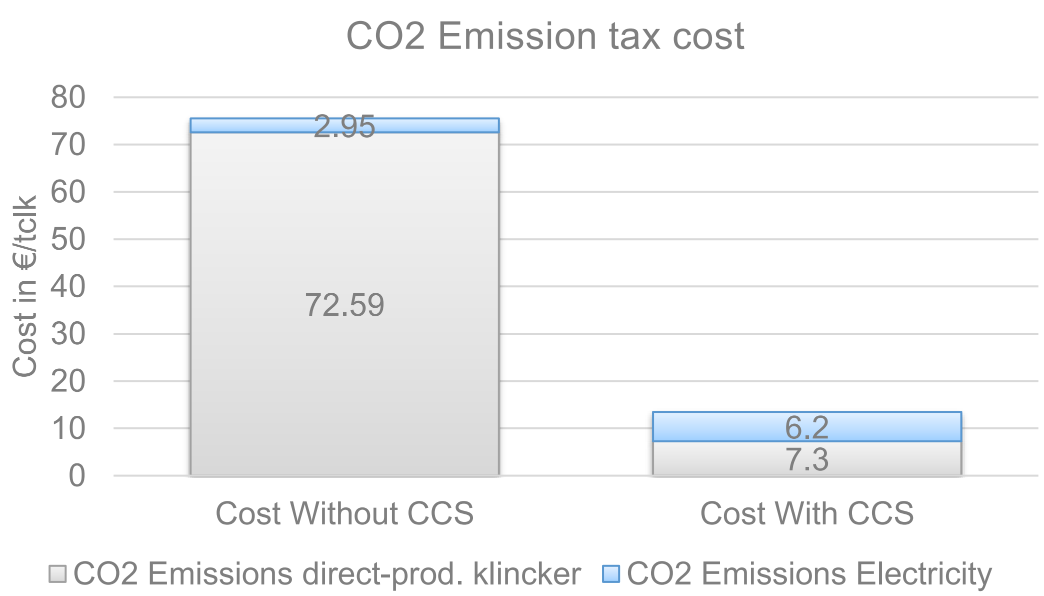
7.5 Scenario I- CO_2 emision taxes

This appendix containing the results reveals that although we covered exclusions in chapter three, which pertained to costs with similar structures that can be evaluated across various locations, we calculated the CO2 emission taxes. This was carried out as an incentive for adopting sustainable technologies, despite needing to be incorporated in the total cost of ownership (TCO) calculation.

Considering CO_2 emission taxes,it is evident that emission taxes can incur significant expenses when capture technologies are not employed, despite not being incorporated into the production cost calculation. Without capture technology, the cost per ton of Clinker produced amounts to 75.38 €/t_{clk}, whereas with CCS technology, it is 13.5 €/t_{clk}.

			PLANT WITHOUT CCS		PLANT WITH CCS	
Variable Cost-CO2 taxes	Tax price	Units	Cost Without CCS	Unit	Cost With CCS	Units
CO2 Emissions price	85.22	€/tCO2				
CO2 Emissions direct-prod. klincker			72.59	€/tclk	7.3	€/tclk
CO2 Emissions Electricity			2.95	€/tclk	6.2	€/tclk
Total			**75.54**	**€/tclk**	**13.49**	**€/tclk**

Table 14- CO_2 emission tax cost.



Graphic 9-CO_2 emission tax cost.

For this scenario, we consider including the costs of the CO2 tax, in such a way as to calculate a total product cost scenario. Will have the following information:

Sensitivity analysis including CO_2 taxes				
Description	**SC I-Without CCS**	**Unit**	**SC I-With CCS**	**Units**
Variable Cost	41.83	€/tclk	67.68	€/tclk
Fixed Cost	18.34	€/tclk	23.62	€/tclk
CAPEX	16.94	€/tclk	24.84	€/tclk
CO_2 Emission Taxes	75.54	€/tclk	8.08	€/tclk
TCO of Clinker	**152.65**	**€/tclk**	**124.22**	**€/tclk**
TCO Cement	**112.50**	**€/tcem**	**91.55**	**€/tcem**

Table 15-TCO including CO2 emissions tax.

Based on the provided information, the table shows that the TCO of Clinker production decreases significantly if include CO_2 taxes from 152.65€/t_{clk} to 124.22€/t_{clk} with the implementation of CCS technology, resulting in a reduction of 28.43/t_{clk} or 18.6%. Similarly, the TCO of cement production decreases from 112.50€/t_{cem} to 91.55€/t_{cem} with the implementation of CCS technology, resulting in a reduction of 19.97€/t_{cem}.

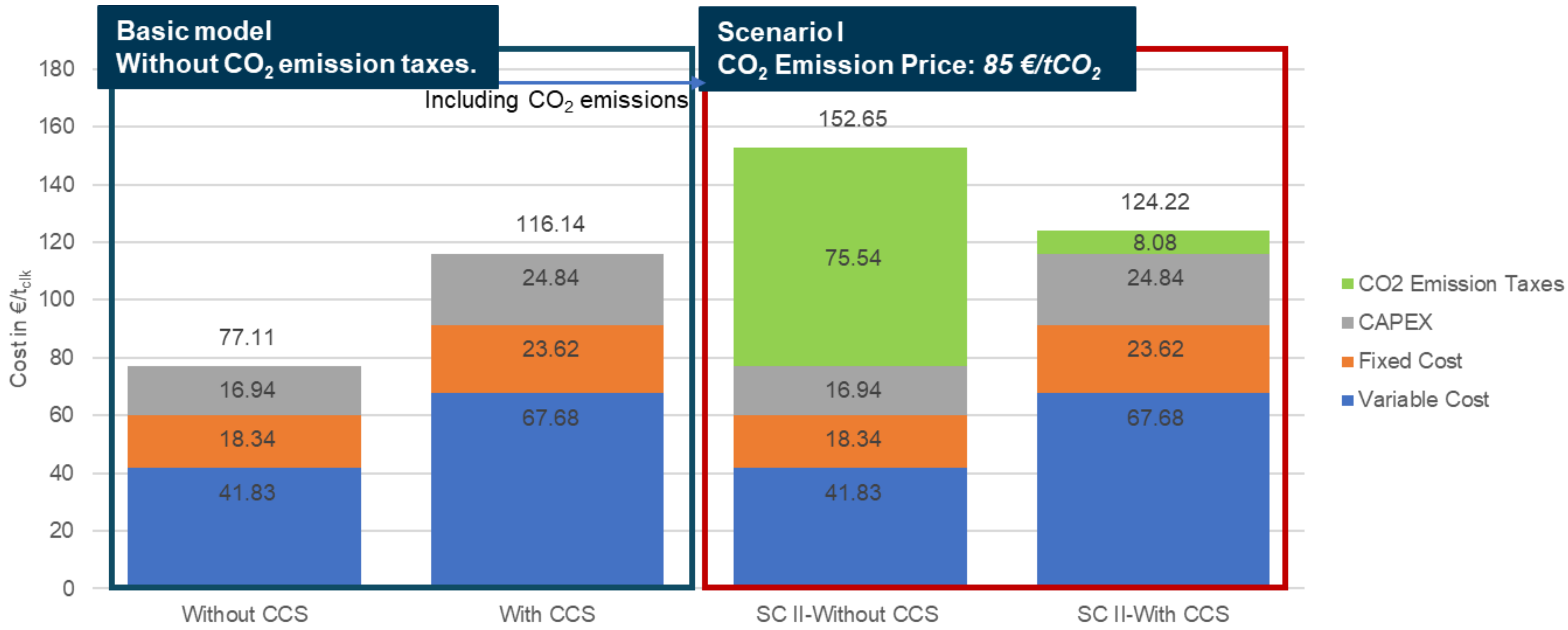
The graph represents a scenario of the TCO of cement production with and without CCS technology for different carbon prices including CO2 taxes. It shows that the TCO of cement production decreases as the carbon price increases for both scenarios, with and without CCS. However, the decrease in the TCO of cement production is more significant with the implementation of CCS technology, resulting in a lower TCO at all carbon prices compared to the scenario without CCS technology.

In conclusion, the scenario suggests that implementing CCS technology in cement production can result in significant cost savings compared to production without CCS technology. The graph indicates that higher carbon prices make CCS technology more economically viable, leading to even more significant cost savings. Therefore, using CCS technology in the cement industry can be a promising solution for reducing carbon emissions and improving the industry's economic viability.

The following graph shows the comparision the base case and scenario I, including CO2 emissions tax in TCO.

7.5.1 Scenario I. CO_2 emission taxes

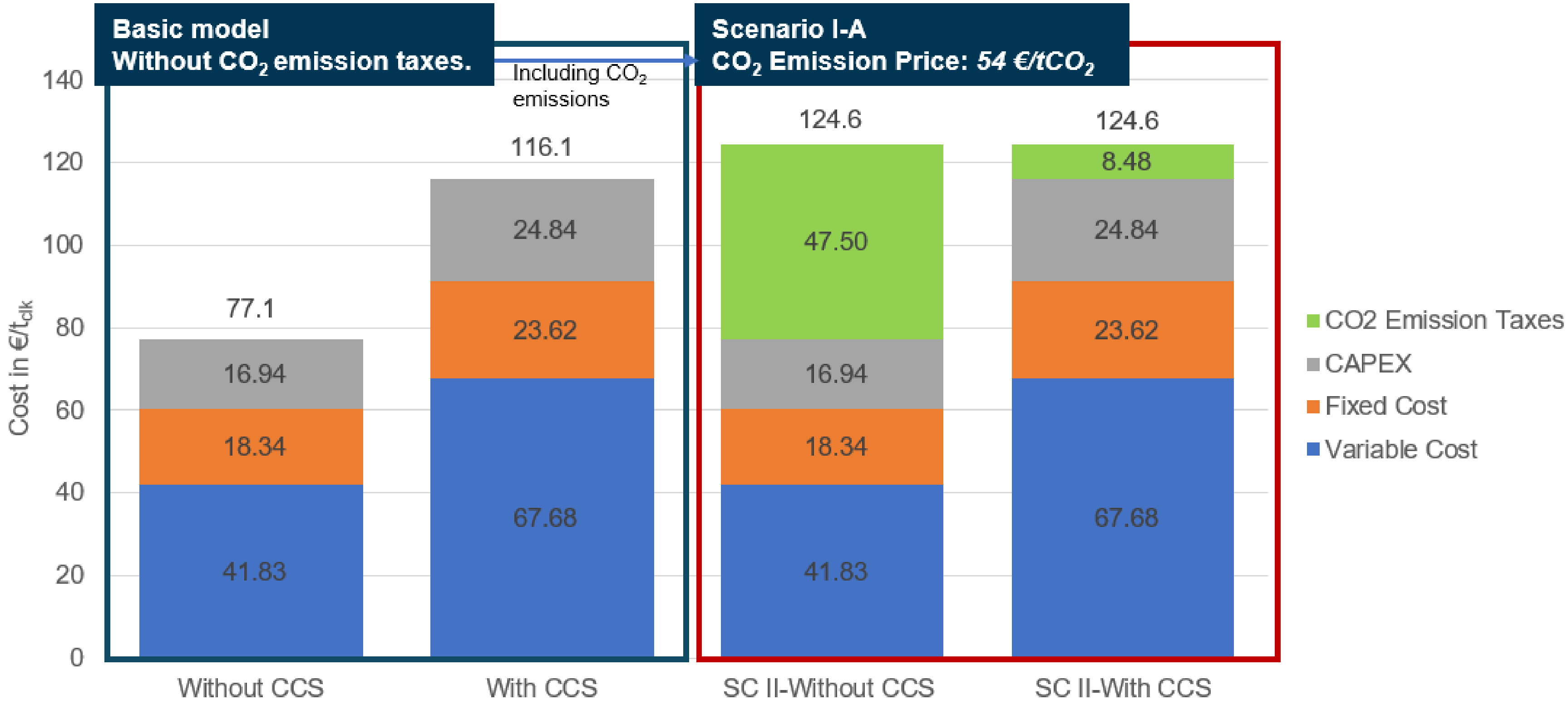
- CO_2 emissions price: 85 €/tCO_2



Graphic 10- Scenario I Comparison breakeven price of CO2 emissions.

7.5.2 The scenario I-A. Breakeven price for CO_2 emission taxes

In the current scenario, the CO2 emission taxes are incorporated as part of the TCO Specifically, it is noted that for a **CO_2 taxes price of 54 €/tCO_2** per ton of CO2, both technologies would have the same TCO, which is to 124. €/t_{clk}.



Graphic 11-Scenario I-A Comparison breakeven price of CO2 emissions.

7.6 Scenario II- Electricity price

The present scenario is created from the analysis of the results in the TCO where it was found that the price of electricity is an influential factor in the cost of cement manufacturing; is the wrost scenario refrence electricity price.

7.6.1 Scenario II.TCO electricity price average 2nd semester 2022

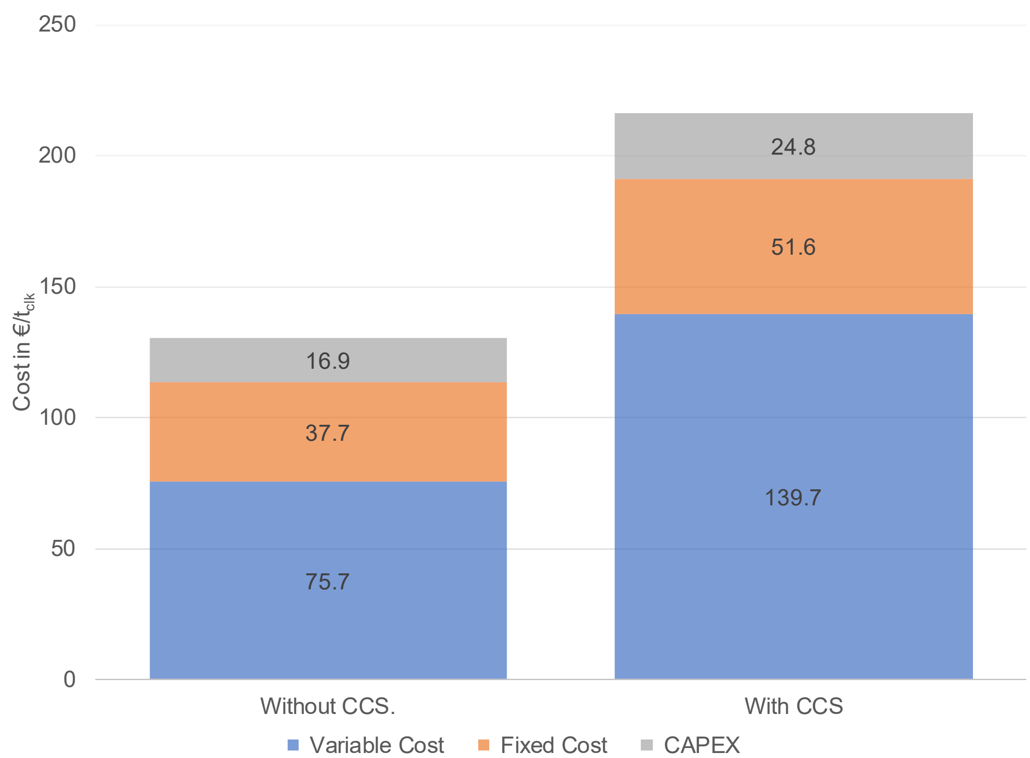
In this analysis, with the electricity price **406.3 €/MWh** is the calculation of the mean based on the top ten values weekly of year 2022 in Germany. [47]
For consult the calculation data you can check to the TCO spreadsheet, electricity scenario spreadsheet.

TCO book electricity scenario spreadsheet:

Based on the scenario presented that with an extreme value of energy price of 406.30 €/MWh, the TCO of Clinker and cement production significantly increases for both the "Without CCS" and "With CCS Oxyfuel" scenarios.

The effect of the increase is more significant in the "With CCS Oxyfuel" scenario, where the variable cost increases from 75.7 €/t_{clk} to 139.7 €/t_{clk}, and the fixed cost increases from 37.7.01 €/t_{clk} to 51.6 €/t_{clk}. The CAPEX also increases for both scenarios, but the effect is more pronounced for the "With CCS Oxyfuel" scenario.

The TCO of Clinker production increases from 130.37 €/t_{clk} to 216.16 €/t_{clk} for the "With CCS Oxyfuel" scenario, while the TCO of cement production increases from 96.08 €/t_{cem} to 159.31 €/t_{cem}.



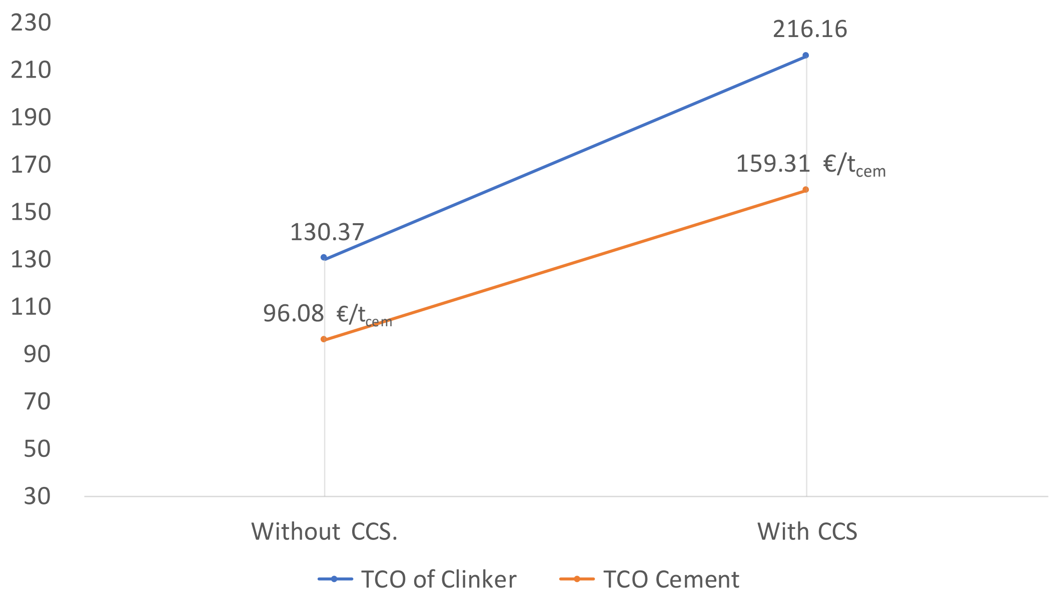
Graphic 12- Scenario II TCO Electricity Price Average 2nd semester 2022 (406.3 €/MWh).

In graph 14 analysis, the scenario is more comprehensive and focuses on showing the variable cost, fixed cost, and CAPEX. It can be observed that the variable cost and fixed cost of cement production increase with the increase in electricity price, and the effect is more significant in the "With CCS Oxyfuel" scenario. The CAPEX also increases for both scenarios, but the effect is more pronounced for the "With CCS Oxyfuel" scenario.

Graph 15, the scenario shows the total cost of ownership (TCO) of Clinker and cement production without discrimination cost. It can be observed that the TCO of Clinker and cement production increases with the increase in electricity price for both scenarios. However, the effect is more pronounced for the "With CCS Oxyfuel" scenario.

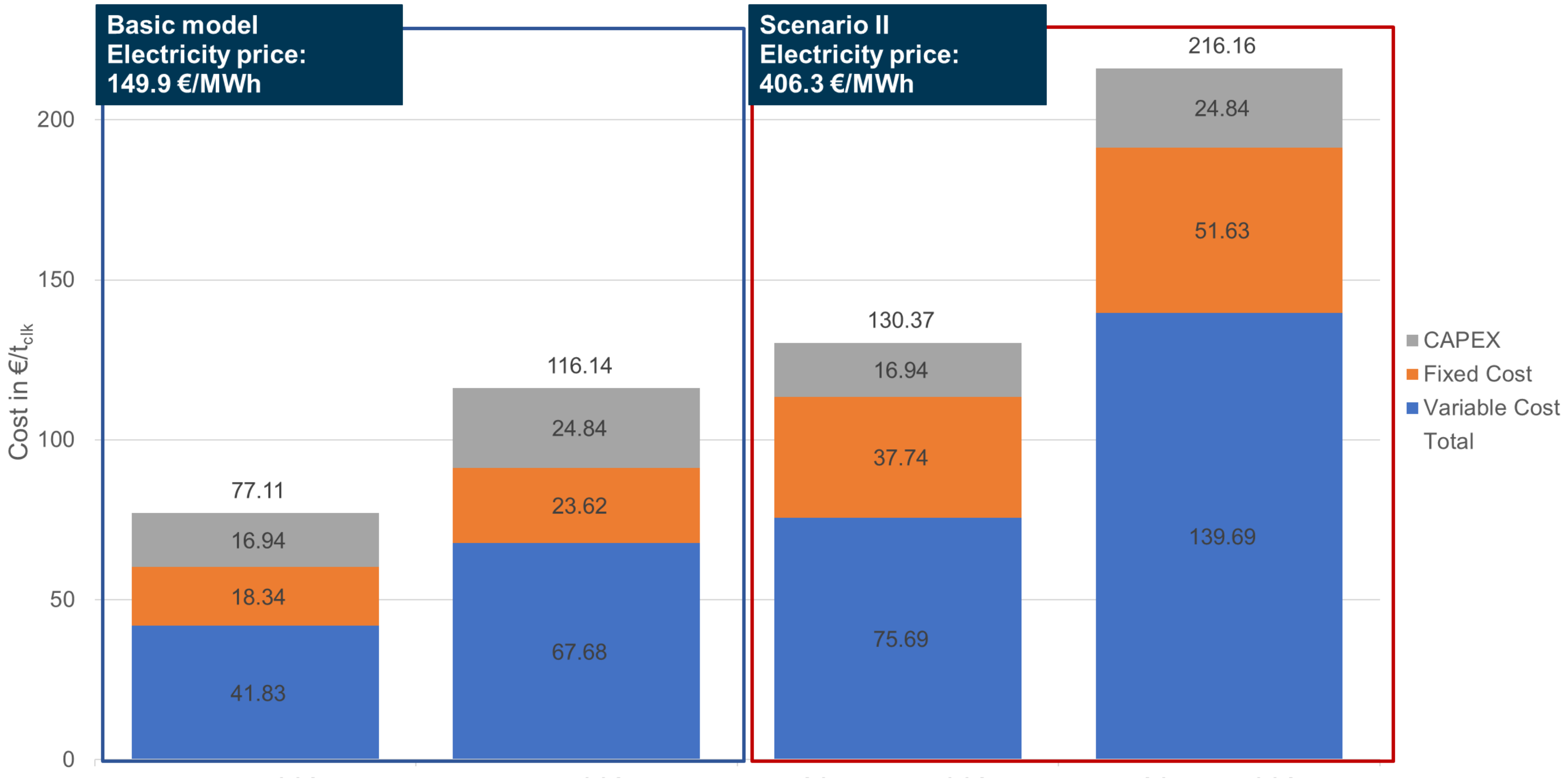
In conclusion, the scenario highlights the significance of electricity price on the cost of cement production, and the analysis provides valuable insights for decision-makers in the cement industry.

The next graphs show the comparision base case and with the variation in the electricity price.



Graphic 13-Scenario II Scenario II TCO Electricity Price Average 2nd semester 2022 (406.3 €/MWh) without discrimination.

Scenario II-A Different electricity average electricity price during 2022



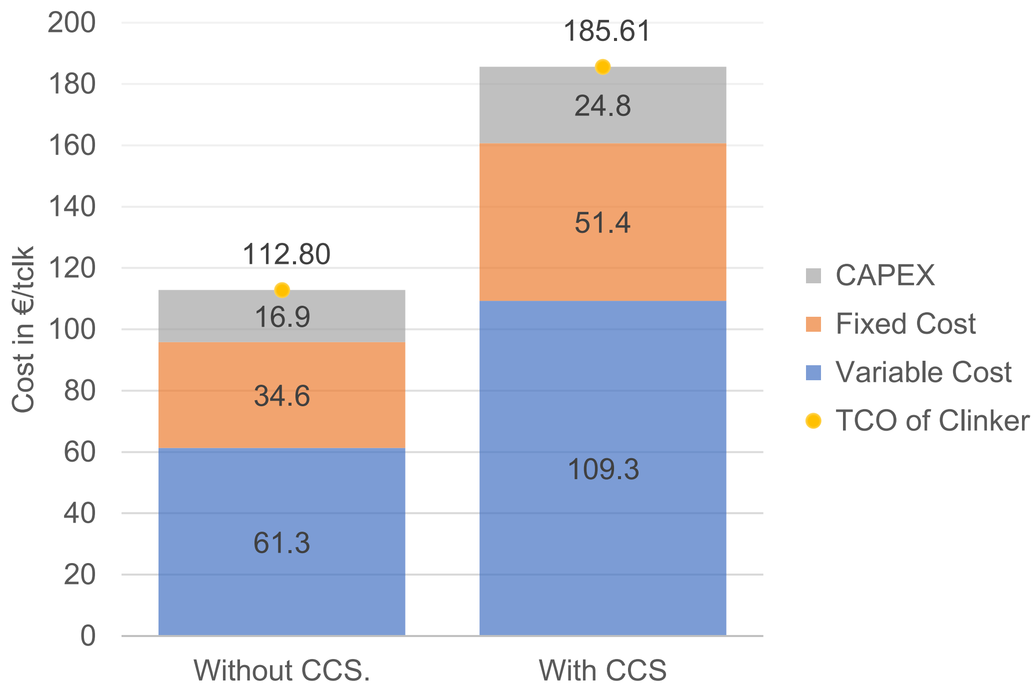
Graphic 14-Scenario II comparison basic model vs pessimist electricity price.

7.6.2 Scenario II-A. Different electricity price-average during 2022

In this analysis, with the electricity price **297.23 €/MWh,** this extreme value is taken as a reference, the average during the year 2022 in Germany. [47]

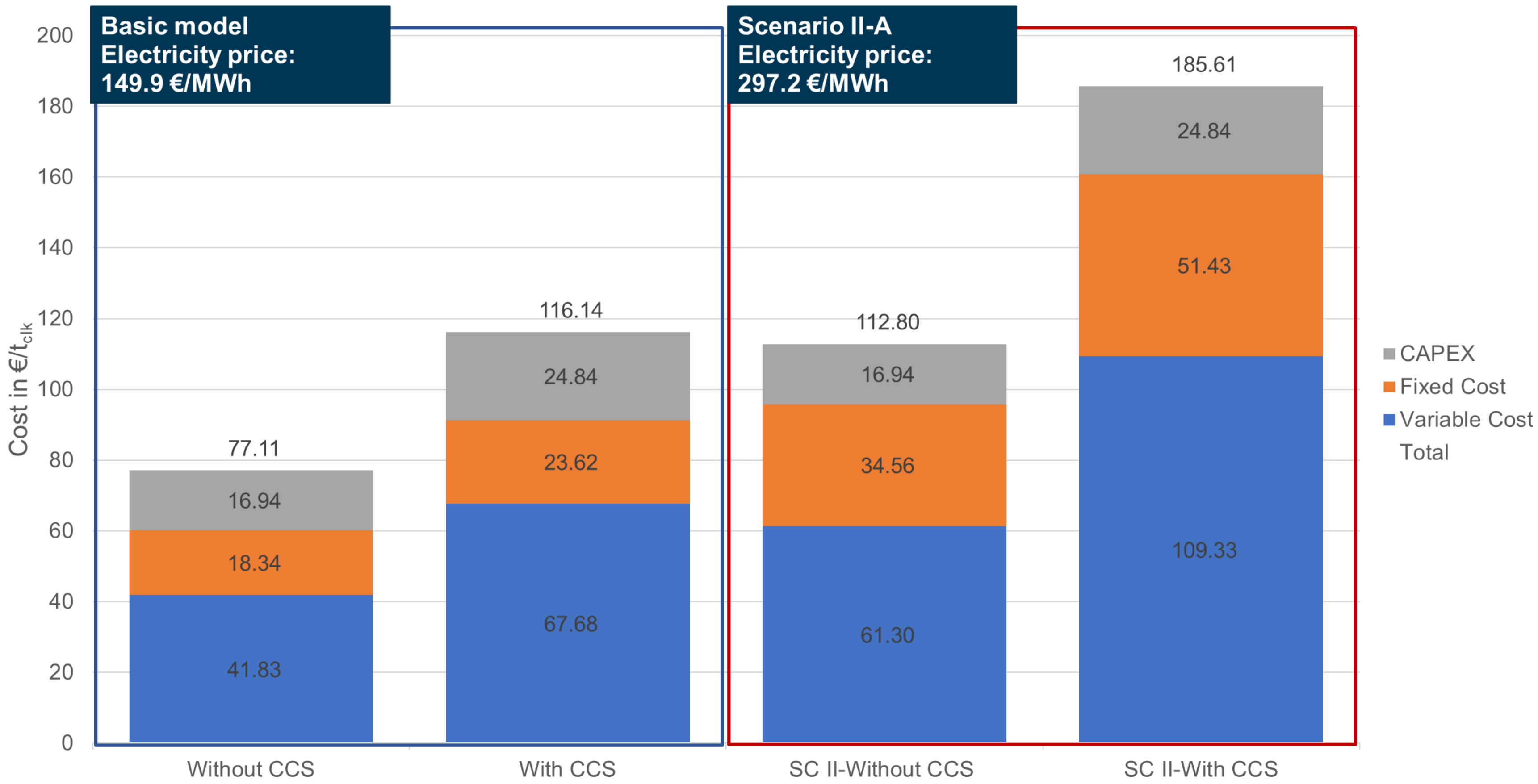
The effect of the increase is more significant in the "With CCS Oxyfuel" scenario, where the variable cost increases from 61.3 €/t_{clk} to 109.3 €/t_{clk}, and the fixed cost increases from 34.6 €/t_{clk} to 51.4 €/t_{clk}. The CAPEX also increases for both scenarios, but the effect is more pronounced for the "With CCS Oxyfuel" scenario.

The TCO of Clinker production increases from 112.8 €/tclk to 216.16 €/tclk for the "With CCS Oxyfuel" scenario, while the TCO of cement production increases from 96.08 €/tcem to 159.31 €/tcem.



Scenario II-Different electricity price-average during 2022

This scenario is a less pessimistic one, based on the average energy price **297.2 €/MWh** in the period from January 2021 to January 2022; but it also shows the influence of the electricity price on the TCO.



Graphic 15. Scenario II-A Comparision with average electiricity price in 2022.

8 CONCLUSIONS

Notably, CO_2 capture technologies are currently only viable for the cement industry in terms of investment cost. However, looking at the horizon of 2050 simultaneously with sustainability issues, it is observed that these technologies will have a critical role in the sector to reduce emissions. This highlights the need for the installation of carbon capture technologies soon.

After analyzing the different carbon capture technologies available, it is concluded that oxyfuel is an advanced option under development and cost-effective for implementation. However, it is essential to note that its application requires addressing particular challenges, including higher energy consumption compared to other technologies. These challenges are:

- Higher energy consumption to produce oxygen: Because oxyfuel requires pure oxygen instead of air for combustion, additional oxygen must be produced, increasing the process's energy consumption. The production of oxygen requires energy, which results in a significant increase in the energy consumption of the process.
- Increased energy consumption due to CO_2 separation: CO_2 capture technology requires the separation of carbon dioxide from the flue gas. This is achieved using solvents or membranes, which require additional energy for the separation process.
- Increased process water consumption due to the need for flue gas purification: The oxyfuel combustion process produces flue gases containing impurities and pollutants, which must be cleaned before being released into the atmosphere. These pollutants are removed by adding process water, which increases process water consumption.

Hence, the price of electricity will be a critical future component for using these technologies, as with the future achievement of fossil fuel phase-out, it becomes necessary to have stable energy costs or agreements that allow operating costs to be maintained at sustainable prices.

From what has been said, the cost of electricity is a crucial factor that must be considered when implementing technologies to reduce the use of fossil fuels. As we strive for a future where renewable energy sources are the norm, it is vital to ensure that electricity prices remain stable or that arrangements are made to maintain sustainable operating costs. The success of these technologies will depend, to a large extent, on the ability to balance the financial burden of the transition to a more sustainable energy system with the benefits it will bring.

The data presented leads us to conclude that adopting oxyfuel technology in the cement industry is a significant step toward achieving sustainability. Its practical adaptability, ease of application, and profitability make it an attractive carbon capture solution for cement manufacturers. The high level of carbon capture efficiency not only reduces the carbon footprint of cement production but also results in a decrease in CO_2 emission taxes. This makes the cement manufacturing process sustainable and environmentally responsible.

Based on the previous, we can conclude that to achieve effective decarbonization and reduction in the use of fossil fuels, it is necessary to simultaneously research and develop alternatives that allow a transition towards the use of alternative fuels and the replacement of Clinker in industrial processes. However, it should be noted that the operational progress and emissions reduction potential of these alternatives will be limited based on the inputs of these materials, which will be reduced due to the increase in the use of sustainable technologies in industrial processes.

In light of the fact that the cost of cement in nations outside the European Union is lower when contrasted with the EU and considering the advancements and usage of sustainable technologies in Europe for cement production, the EU has established the Carbon Border Adjustment Mechanism (CBAM). This mechanism will initially be applied to imported goods and raw materials that are manufactured using high levels of carbon and are at a considerable risk of contributing to carbon leakage, including cement, iron and steel, aluminum, fertilizers, electricity, and hydrogen. Upon full implementation, CBAM will cover more than half of the emissions generated by the sectors governed by the EU Emissions Trading System (ETS). According to the current political agreement, the CBAM will initiate its transitional phase on October 1, 2023 [48].

From this it is necessary to say that all stakeholders, including political leaders, manufacturers, and consumers, work together in a concerted effort to prioritize sustainability and innovation in cement production. This entails the implementation of economic incentives that bridge the gap in the adoption of carbon capture technologies, while emphasizing the need for investments that balance both environmental sustainability and financial viability. It has been demonstrated that this approach has a significant economic impact on the cost of the product. Although taxes may be considered financial issues that are not directly included in the cost, it is essential to note that the success of implementing sustainable practices and technologies depends on both the cost of the product and its environmental sustainability and financial viability. Therefore, it is crucial to prioritize both aspects to ensure that industries can achieve a sustainable and profitable balance without negatively impacting their bottom line.

These points highlight the need for a holistic approach to sustainable cement production that considers environmental, economic, and social factors. The cement industry can reduce its carbon footprint and contribute to a more sustainable future by adopting sustainable technologies and practices. As more cement manufacturers recognize the benefits of this technology, we can expect to see a shift towards more sustainable and environmentally friendly methods of cement production.

Concerning the above, there is a need to conduct in-depth research and obtain financial information on existing electrified equipment. Some of these still need to be fully implemented and are being evaluated as pilot technologies or are not widely used. Research in this area can serve as an alternative and significant inclusion in different processes to complement sustainable technologies, thereby increasing the possibilities of decarbonization.

Based on the preceding analysis, it was found limiting in data collection that the lack of availability of economic data to the public due to confidentiality issues of the companies creates a significant gap in economic research. Access to this information also limits the use of other financial calculation methods. Although confidentiality is fundamental for companies, finding ways to balance privacy and the need for transparency and accessibility of economic data for theoretical research is crucial for making effective decisions and promoting economic growth.

9 RECOMMENDATIONS

Through the present research, the following recommendations are suggested either for expansion of the present or for diversification in future work.

9.1 Emerging industrial uses of CO_2

Considering that the most advanced decarbonization technologies today are carbon capture and storage processes, research can be done on the use of CO_2 in industrial use, for example:

- "Chemical conversion to high value-added products" Enhanced Coal Bed Methane Recovery
- Enhanced Geothermal Systems (using CO_2 as a working fluid)
- Power Generation with CO_2 as a working fluid
- Polymer Processing
- Power-to-X conversions
- Algal bio-fixation and bio- fuel production
- Bauxite residue processing
- Carbonate mineralization (aggregate production)
- CO_2 concrete curing
- Chemical conversion to high value-added products" [22]

9.2 Use of alternative fuels in the cement industry

There is a great variety of alternative fuels, and, in this study, it is recommended to examine the following ones, as they present specific advances in the global cement industry:

- Climafuel or Enerfuel is a waste-derived fuel, produced using household and commercial waste that would otherwise end up in landfill. [49]
- Hydrogen in kiln: The injection of hydrogen into the cement kilns acts as a catalyst, which would allow CEMEX to optimize the combustion process and increase the use of alternative fuels and thus decrease the consumption of fossil fuels. [50]
- CDM (Clean Development Mechanisms): "In this case, rice husks are mainly used in the production process of Clinker, the main input for the manufacture of cement." [51]
- Rüdersdorf Carbon Neutral Alliance, which includes four consortiums and over 20 partners. The alliance is working to turn our Rüdersdorf cement plant, in Germany, into the first net-zero CO_2 plant ever.
  - Cement plant with carbon capture unit
  - Renewable energy consumption
  - Electrolyzer for H2 production
  - E-reserve water gas shift reactor
  - CO electrolyzer
  - Fischer Tropsch reactor
  - Production of more sustainable fuels
  - Production build materials
  - Preparation of CO_2 for transport, such a ship rail or a purpose build pipeline. [49]

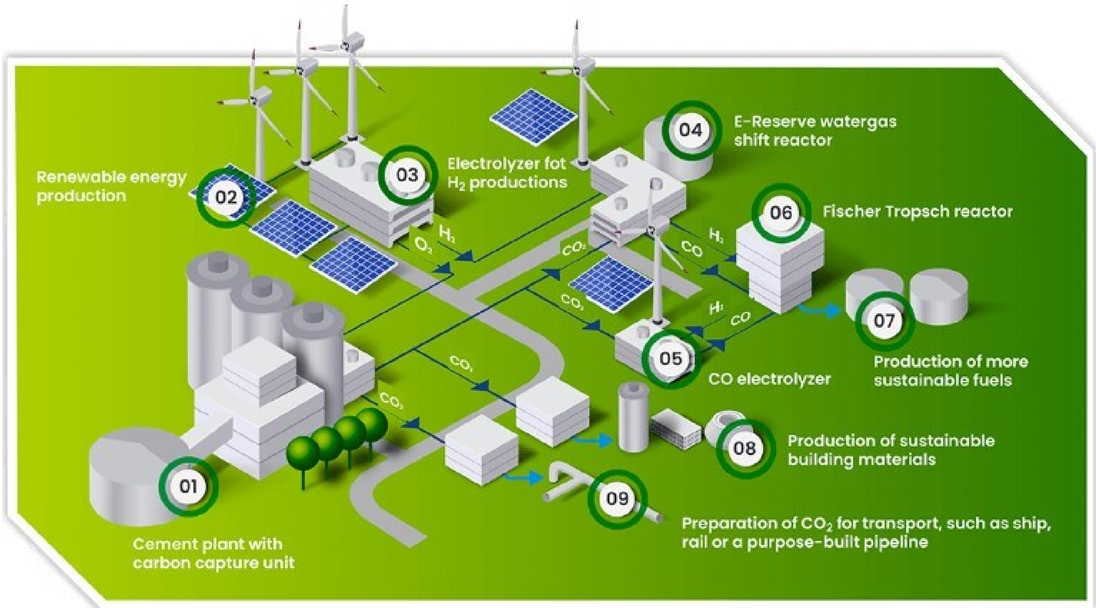


Figure 25: Rüdersdorf Carbon Neutral Alliance [49]

- CDM (Clean Development Mechanisms): "In this case, rice husks are mainly used in the production process of Clinker, the main input for the manufacture of cement." [51]

9.3 Transportation of CO_2 storage

The transport of carbon capture storage by ship, rail, road, or pipelines. [52]

9.4 Electrification-Electrified equipment

The research has predominantly identified such equipment associated with this technology:

- "RotoDynamic Heater (RDH) is the only electric process heating technology able to reach 1700°C without burning fossil fuels. In RDH, air, nitrogen and process gases are heated to high temperatures and the heated gas is used outside the heater to replace the burning of fossil fuels in process heating. It’s the only electric technology that can replace fossil-fired furnaces and kilns with electric heating in industrial processes." [53]

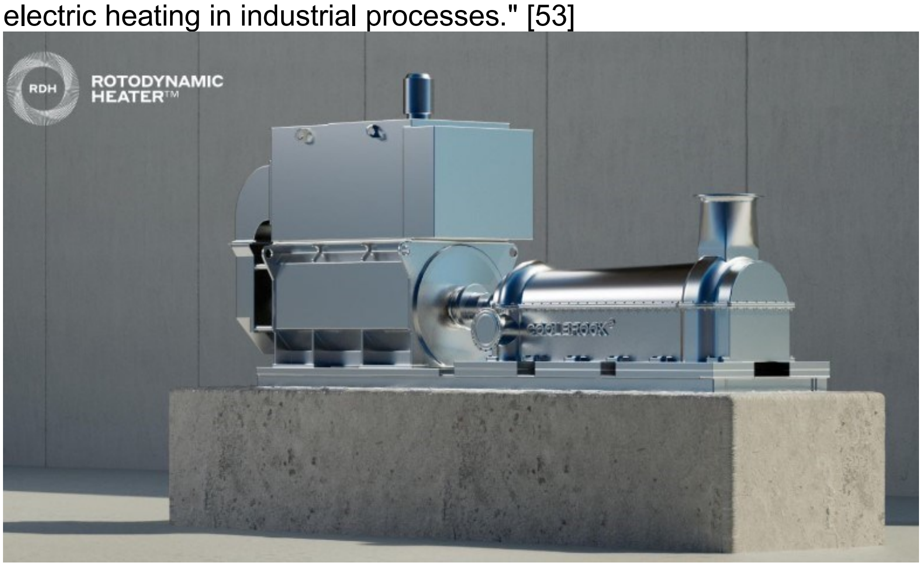


Figure 26: Rotodynamic Heater RDH [53]

- Heavy Machinery: Keestrack has now introduced the ZERO drive, with which machines do **not require an integrated combustion engine** at all. Most mobile crushing and screening plants, as well as some necessary hydraulic systems, are driven by electric motors [54].

9.5 Alternative costing method

The proposed suggestion entails acquitting the knowledge of another method such as NPV.

Summary:
The **TCO Method** is utilized to evaluate the long-term value of a purchase to an individual or corporation by assessing its total cost of ownership. Corporations primarily use it to analyze business deals, while individuals use it to evaluate potential purchases, according to theory it is often used in procurement.

Key points:
- TCO Method helps in evaluating the long-term value of a purchase.
- It is used by both corporations and individuals for assessing business deals and potential purchases, respectively.

Disadvantages:
- TCO Method does not consider the time value of money or risk.
- It fails to consider the option value of more flexible systems.
- It only considers the costs while disregarding the benefits.

NPV Method Summary
The NPV calculation is a comprehensive formula that considers several financial aspects, such as cash flows, the time value of money, the discount rate over the life of the project (usually the weighted average cost of capital (WAAC)), the terminal value and the residual value.

Key points:
- NPV calculation assists investors in determining the current value they are willing to pay for a future cash flow.
- It involves discounting a future stream of cash flows to their present value.

Disadvantages:
- the difficulty in accurately determining a discount rate that represents the actual risk premium of the investment; may not be difficult for a financial expert.
- Obtaining the necessary data for the calculation often requires access to historical data or assumptions based on actual financial data from companies within the industry.

TCO is a way to evaluate the long-term value of a purchase for a company or individual, considering the total cost of ownership. At the same time NPV is a technique for valuing investment projects that consider the discounted future cash flows to their net present value, considering the discount rate and inflation.

In summary, TCO focuses on the long-term costs of a product or service, while NPV focuses on the profitability or net present value of an investment in a project.

To make a well-informed decision, it is advisable to employ both Total Cost of Ownership (TCO), Net Present Value (NPV) and Return on Investment (ROI) in conjunction. **This approach enables an assessment of the level of risk tolerance based on the projected returns and total costs associated with the various project options**. As such, a comprehensive analysis of the investment alternatives can be conducted, resulting in a more informed decision-making process.

9.6 Supplement to the Corporate Value Chain (Scope 3)

Accounting & Reporting Standard; Regarding greenhouse gas emissions, Scope 3 emissions refer to indirect emissions that are generated in the supply chain and are associated with the activities of an organization but occur outside of its direct operational control. These emissions result from the activities of suppliers, customers, and other actors in the organization's value chain. It is important to note that Scope 3 emissions can make up a significant portion of an organization's overall carbon footprint. Therefore, it is recommended that organizations take steps to measure and reduce their Scope 3 emissions. This can be achieved by encouraging suppliers to reduce their emissions, selecting suppliers with lower carbon footprints, and implementing sustainable practices throughout the entire value chain. By doing so, organizations can reduce their carbon footprint and contribute to a more sustainable supply chain. [55]

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