# CARBON CAPTURE AND STORAGE IN INDUSTRIAL PRODUCT VALUE CHAIN

An economic assessment of the impact of carbon capture and storage in the industrial product value chain: from industrial production to final product.

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by

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It was worth it.

*Elda Rodríguez*

*Delft, October 2020*

# EXECUTIVE SUMMARY

## Context

The industry is the second-largest source of $CO_2$ emissions accounting for one-quarter of direct $CO_2$ emissions in 2017. The demand for industrial products has increased in the past two decades and is expected to still increase over the next decades since it is tied to economic development, global population, and urbanization. Nevertheless, as an economy develops more products are consumed and, in turn, more energy consumption, and more $CO_2$ is emitted by the industry. To accomplish the Paris Agreement goals to battle climate change, the industry must emit less $CO_2$ regardless of the expected growth in product demand.

$CO_2$ emissions from industry are hard to abate since process emissions cannot be avoided or reduced by the use of biomass, low-carbon feedstock, low-carbon fuel, or electricity. Carbon capture and storage (CCS) offers a solution for reducing $CO_2$ process emissions in which $CO_2$ is captured, purified, and compressed to be transported for long-term storage. However, CCS application in the industry can lead to a substantial increment in the cost of industrial plants having an impact on industrial consumers and, in turn, end-consumers of products through a value chain.

## Research objective

There is a lack of research where the implementation of CCS on multiple industries to produce a common final product as well as an assessment of $CO_2$ emissions reduction along a value chain. The purpose of this study is to assess the product cost impact on final consumers. For instance, people do not consume cement directly, rather, they do either through a bridge (i.e., driving way to the office) or purchasing a house in which materials derived from cement are used for its construction. Additionally, to assess the $CO_2$ emissions reduction through the value chain when CCS is implemented in the industry. The main research question is:

***To what extent does CCS implementation in primary production translates the cost and the $CO_2$ emission reduction across the industry value chain from industrial production to the final product?***

In this study, the direct $CO_2$ emissions and the production cost of several products that conform to the value chain are evaluated when CCS is implemented in industrial production. A carbon footprint assessment and an economic assessment are set to answer the sub-questions:

- *$Q_1$: What are the key technical factors that influence final product costs and their $CO_2$ emission reduction when CCS is implemented in the production of industrial products?*

- *$Q_2$: To what extent do cost allocation approaches impact the CCS cost across the value chain?*

## Methodology

This study aims to assess to what extend CCS application in industries (e.g., cement, steel, chemicals, and oil refining) would impact production costs as well as $CO_2$ emission reduction through their value chain. In this context, a value chain is composed of three main elements; primary product, intermediate product, and final product. A primary product derived from an energy-intensive production process and where CCS is implemented. An intermediate product where the primary product is used as part of its materials. A final product that is consumed directly by a final consumer (e.g., people). To this end, this research is conducted through three case studies. The first case study evaluated a value chain related to the construction sector where a beam bridge represents an example of a frequent type of infrastructure in which both cement and steel are used as construction material. The second case study evaluated a value chain related to the farming sector in which nitrogen fertilizers are consumed and where ammonia (i.e., chemical industry product) is used in its production. The third case study evaluated a value chain related to the oil refining sector and the industry of polymers where a foam mattress represents an example of the use of polymers where propylene (i.e., oil refinery product) is used in its production.

The value chains are evaluated in a gate-to-gate analysis (i.e., primary production gate to final production gate) where the extraction of raw materials and delivery to production facilities have been excluded from the analysis as well as final product distribution, commercialization, usage, and final disposal.

$CO_2$ emissions estimation for the carbon footprint assessment is estimated under scope 1 (i.e., direct emissions from the combustion of fossil fuel and process emissions). Indirect emissions (i.e., due to electricity imported from the grid, heat, and steam produced outside of the production facilities) have been excluded from the analysis. Also, $CO_2$ emissions from transport between primary production facilities to intermediate and/or final product manufacturers are included. The $CO_2$ emissions (with and without CCS) are estimated sequentially at each stage of the value chain in primary production, intermediate production, and transport emissions.

Production cost estimation for the economic assessment consists of capital cost (CAPEX) and operating costs (OPEX). CAPEX is expressed in terms of total requirement cost (TRC). Fixed OPEX includes maintenance, labor costs, and administrative costs. Variable OPEX includes raw material costs and utilities such as electricity and fuel costs. Electricity (i.e., for non-households), natural gas, and diesel 2018 prices in the Netherlands are used for variable OPEX estimation. Delivery costs (i.e., from primary production facilities to intermediate or final production facilities) are included. All costs are updated and expressed in $€_{2018}$ using the Chemical Engineering Plant Cost Index (CEPCI). The cost estimation (with and without CCS) is estimated sequentially at each stage of the value chain in primary production cost, intermediate production cost, transport costs, and final production cost.

CCS cost in cement, steel, and ammonia/urea production was allocated directly to the products since by-products are non-existence. In propylene production, different cost allocation approaches using physical measures such as mass-based and energy-based allocation were explored. Moreover, those approaches were used to allocate the CCS cost in the product streams and the process streams.

A sensitivity analysis was performed to provide a better understanding of the economic performance indicators when there is uncertainty in fuel cost and $CO_2$ capture technologies investment cost along the time.

## Results

The results were presented to answer the sub-questions.

- $Q_1$: The key technical factors that influence the primary production cost when CCS is implemented are either the fuel or the electricity that is consumed by the capture unit. Another factor that influences the final product cost is the number of elements in the value chain and the fraction or contribution of the primary product cost as material cost in the final product cost.

- $Q_2$: It can be concluded that there is not a unique approach to cost allocation that fits all industries and cases. Additionally, evaluating different allocation approaches is applicable where primary production yields more than one product with a commercial value. In this case, different allocation approaches are considered to allocate the CCS cost to the products. Even when CCS cost allocates in primary products vary based on the cost allocation, the final product will have a negligible impact on its production cost. The allocation of CCS cost is not limited to primary production. It is also related to the breakdown of the intermediate and final production costs

In the sensitivity analysis, it was observed that the electricity-intensive capture technologies are sensitive to a variation in the electricity cost having an impact on the production cost, capture cost and $CO_2$ avoided cost or natural cost. On the other hand, the capture technologies that require fossil fuel are sensitive to a variation in the coal and natural gas costs. Besides, the production cost, capture cost, and $CO_2$ avoided cost are less sensitive to a variation of CAPEX of capture technology compared to variations in electricity and natural gas costs.

This research provides insight into the implementation of CCS in industrial production from a consumer perspective (i.e., the cost impact on the final product). The impact of implementing CCS in two different industries (e.g., cement and steel) to produce a final product is analyzed. Also, this research provides insight into CCS implementation in industries with high consumption products. It can be concluded that implementing CCS in industrial processes offers a solution to decarbonize industrial processes with a small impact on the final product cost.

## Limitations

In this research, several limitations to the results were presented. These limitations could be explored in future research.

- $CO_2$ emissions are estimated under scope 1 (i.e., direct emissions including energy-related and process emissions). Indirect emissions were excluded.

- The industries where electricity is generated on-site (e.g., steel and oil refinery) did not consider revenues from exporting electricity to the grid.

- The system boundaries of the case studies were defined based on a gate-to-gate perspective.

- A simplified ammonia/urea production plant was assessed. The reference plant did not consider the production of by-products.

- Oil refinery production costs did not consider the raw material cost (e.g., crude price) and market prices of the products.

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# 1. INTRODUCTION

## 1.1 CONTEXT

In 2017, industry accounted for about 40% of global energy consumption and one-quarter of direct $CO_2$ emissions (i.e., energy-related and process emissions) being the second-largest source of $CO_2$ emissions (IEA, 2019). In this context, the industry represents the energy-intensive industries (i.e., heavily depend on energy inputs). Steel, cement, and the chemical sector are the highest-emitting industries (IEA, 2019).

The Paris Agreement was established to battle climate change, to limit the global temperature increase, and to enhance actions for a low carbon future (UNFCCC, 2020). To accomplish the goals, the greenhouse gas emissions produced by human activities are projected to decrease by about 25% by 2030 and net-zero by 2070 (IPCC, 2018).

The demand for industrial products has significantly increased in the past two decades and is expected to still increase over the next decades. (IEA, 2020). Product demand is tied to global population growth, economic development, and urbanization (IEA, 2020). For instance, cement and steel are used to build infrastructure, fertilizer is vital for crops to feed the growing population, and plastics are part of everyday products (IEA, 2019). As an economy develops more products are consumed, thus, the demand for materials determines the energy consumption by the industry and its $CO_2$ emissions. Furthermore, the industry must emit less $CO_2$ to meet the climate goals regardless of expected growth in demand (IEA, 2020).

There are some emission reduction measures for the industrial sector such as; use of biomass, energy efficiency improvements in the processes, use of low-carbon feedstock, switching from fossil fuel to low-carbon fuel or electricity, and heat generation through renewable-based power instead of burning fossil fuels. However, reducing $CO_2$ emissions is challenging from a technical and economic perspective. Some examples are; an increase in the electricity demand, availability, and cost of biomass and renewable electricity. Also, industrial processes require high-temperature heat making less convenient switching to renewable-based heating technologies compared to processes where low-temperature heat is required (e.g., food industry) (IEA, 2016) (IEA, 2020). Despite the measures already mentioned, process emissions (i.e., $CO_2$ is an inherent product of chemical reactions) cannot be avoided or reduced. For instance, 65% of $CO_2$ emissions generated by the cement production result from the calcination of limestone (IEA, 2019).

Carbon capture and storage (CCS) is a solution for reducing $CO_2$ process emissions. $CO_2$ released from calcination of limestone in cement production and iron ore reduction in steel production can only be reduced utilizing $CO_2$ capture (IEA, 2016). For instance, through CCS, the $CO_2$ emissions in cement production can be reduced by 60 to 70%, in steel production by 45% to 60%, and in fertilizer production (e.g., ammonia) could be reduced by 70% (IEA, 2016). CCS consists of $CO_2$ capture from both energy-related and process emissions point sources (e.g., furnaces, flue gas). Then, the $CO_2$ stream is purified and compressed to be transported (i.e., via pipeline) for long-term storage (IEA, 2019). Nowadays, 19 large-scale CCS projects are applied in industrial processes and are expected to play an important role in the industry decarbonization and $CO_2$ emission reductions in the upcoming years to pursue the goals of the Paris Agreement (IEA, 2020). However, CCS applications in the industry can lead to a substantial increment in the cost of industrial plants (e.g., cement, steel, and chemicals). For instance, the cost of cement production could increase by 40% to 105% (i.e., depending on (IEA, 2016). Voldsund et al., 2018 reported a production cost increase by 65% to 95%.

Cement, steel, and some chemical industries operate at a low-profit margin. Also, these products (i.e., except for cement) are traded globally and are price-takers in international markets. (IEA, 2019). Therefore, an increment in the production cost, despite CCS provides a solution to reduce $CO_2$ emissions, could lead to economic repercussions, less product competitiveness, and producers' reluctance to adopt and apply CCS in industrial processes (IEA, 2016). According to IEA (2016,p.88): “a combination of regulation, incentive mechanisms and consumer demand for clean product could provide a framework to support the large capital investment involved in CCS, and help to manage the impact on competitiveness for plants that reduce emissions”. For instance, a cap on the $CO_2$ emissions and a carbon tax (i.e., as long as the cost for releasing $CO_2$ emissions is higher than implementing CCS cost) would push producers to adopt CCS (IEA, 2016). Other mechanisms such as a fiscal incentive (e.g., investment tax credits) would encourage producers to invest in CCS technology (IEA, 2016). A consumer-led demand would help to partially deal with the increase in production cost through a consumer’s willingness to pay more for certain products (IEA, 2016). This demand could be impulse by a carbon labeling scheme to influence consumer purchase habits to consider low-carbon alternatives (Ji et al., 2017) (IEA, 2016) or through an extensive public awareness regarding $CO_2$ emissions (IEA, 2016). It would not be enough to implement either a consumer-led demand or incentive mechanism for producers to pursue CCS applications in energy-intensive industries. According to IEA (2016,p.89): “the solution might lie in a concept of layered incentives, whereby the additional cost of CCS is covered throughout the chain’’. In this context, a chain could be described as a system made up of three elements; producer of industrial products (e.g., cement producer), an industrial consumer (e.g., construction sector consuming cement), and the end-consumer (e.g., people buying a house) (IEA, 2016). For instance, the increase in the cement production cost, by CCS implementation, may have a minor impact on a residential building cost as cement represents one of the many construction materials (IEA, 2016)(Rootzén & Johnsson, 2017). In addition, it is also important to evaluate the impact of CCS when is implemented in the production of industrial products from the end-consumer perspective. For instance, if the end-user would bate the cost and see a benefit in reducing the carbon footprint of the product.

# 1.2 LITERATURE REVIEW

The cost related to CCS implementation in the industrial sector has been a matter of several studies. Leeson et al., 2017 presented an extensive literature review regarding CCS applied in the industrial sector in the period 2008 to 2014. The study reviewed several books, journal articles, and published expert reports about the technology of carbon capture, policy changes behind carbon capture, and industrial application for iron and steel, cement, oil refining, and pulp and paper industries. Just a few papers investigated the economics of CCS on industrial systems. Moreover, in the study cost date has gathered and used to model a projected cost per tonne of $CO_2$ avoided, when CSS is implemented, until 2050 for industries (e.g., cement, iron and steel, and petroleum refining). Farrel et al., 2019 proposed a methodology to standardize the cement production cost with and without CCS considering different capture technology options available for the cement industry (e.g., post-combustion capture, oxy-combustion, and cryogenic carbon capture).

Further studies analyzed Levelized costs, operational costs, and capital cost, among others. For instance, Psarras et al., 2017 developed a methodology to determine the levelized cost per tonne $CO_2$ captured across different industrial processes (e.g., aluminum, ammonia synthesis, cement, glass, iron and steel, pulp and paper). Another study performed by Onarheim et al., 2016 focus on the operational costs, capital investment costs, and technical aspects of retrofitting a modern pulp mill through a post-combustion capture based on amide absorption. Andersson et al., 2016 studied comparison of the cost for future post-combustion CCS operating with different stripper reboiler temperatures at an oil refinery.

The International Energy Agency Greenhouse Gas R&D program collaborates with different academic institutions and consultancies to elaborate techno-economic assessments for several capture technologies (IEAGHG, 2020) to evaluate its cost of retrofitting $CO_2$ capture in different industries. The cement industry is assessed in (IEAGHG, 2013a) technical report. In this study, a technical and economic evaluation of CCS application in cement plants (i.e., dry kiln process) is performed. Oxyfuel and post-combustion (e.g., chemical solvent absorption) capture technologies were considered in the evaluation. The iron and steel industry is evaluated in the (IEAGHG, 2013b) technical report. This study evaluated the steel production cost when CCS is implemented in an integrated steel mill. Post-combustion (i.e., MEA as solvent) and oxygen are blown blast furnace (OBF) with CO2 capture (i.e., MDEA/Pz as solvent) capture technologies were considered in the study. The chemical industry is evaluated in (IEAGHG, 2017a) technical report. This study presents two studies; ammonia/urea production using natural gas as feedstock and fuel (i.e., Haber-Bosch process), and methanol production from natural gas. In both studies, post-combustion (i.e., MEA as solvent) capture technology is considered in the techno-economic evaluation. Furthermore, hydrogen production (i.e., steam methane reformer) using natural gas as feedstock is studied in (IEAGHG, 2017b). The findings of this report were used in the formerly mentioned studies (e.g., ammonia/urea and methanol production). A techno-economic evaluation of $CO_2$ capture in an oil refinery is studied in (IEAGHG, 2017c). In this report, post-combustion based on MEA solvent technology is evaluated. In all the technical reports mentioned above the findings are reported as following; production cost (e.g., cost per tonne of cement) with and without CCS, increase in the production cost (i.e., due to CCS implementation), the $CO_2$ avoidance cost (e.g., cost per tonne of $CO_2$ avoided), the generated $CO_2$ emissions before and after capture as well as the $CO_2$ avoided emissions.

There are similar techno-economic assessments to those carried out by IEAGHG evaluating the cement industry. The difference consists of considering further capture technologies. Voldsund et al., 2018 evaluated the cement production (i.e., dry kiln process) considering post-combustion (e.g., MEA solvent), oxyfuel, chilled ammonia process, membrane-assisted $CO_2$ liquefaction, and calcium-looping (i.e., tail-end and integrated) as capture technologies.

All the studies mentioned above are focus on cost assessment when CCS is solely implemented in the industrial process. However, those studies do not evaluate the impact cost on the other elements of the chain (e.g., industrial consumer end-consumer). Rootzén & Johnsson, 2017 investigated how the cost of reducing $CO_2$ emission by CCS implementation in cement production influenced the cost across the value chain from cement production to the construction of a residential building. The study concluded that the increment in the residential building construction cost is little (i.e., about 1%) even when the cement production cost is doubled after the adoption of CCS in the production process. The study demonstrated that cement represents one of the many materials used for construction (i.e., cement used to produce concrete and concrete used as a building material). Moreover, the material cost represents only a share of the total construction cost. A similar study performed by Rootzén & Johnsson, 2016 investigated a value chain where steel production is involved. They investigated how the cost of reducing $CO_2$ emission by CCS implementation in steel production influenced the cost across the value chain from steel supply to a passenger car. The study concluded that the increment in a passenger car is minimum (i.e., less than 0.5%) even when the steel production cost increased by about 35%. This finding was supported by the assumption of steel represents one of the many materials required for car manufacture. Karlsson et al., 2020 analyzed construction supply chains in Swedish construction projects intending to reach net-zero $CO_2$ emissions. The study compared the use of different materials (e.g., steel, concrete, and asphalt) considering different emission reduction measures (e.g., electrification and CCS) in the production of materials.

## 1.3 KNOWLEDGE GAPS

Based on the literature review, it was found most of the previous studies had as a subject of study; carbon capture technology applications, improvements in the technology itself, and CCS implementation costs per $CO_2$ emissions avoided along the industrial process. Nearly all studies are focused on CCS implementation solely on the industrial its selves (e.g., cement, steel, and chemical industries) without addressing how the increment in the production cost of industrial products impact the end product (i.e., from industrial products to an end-consumer). Similar studies to Rootzén & Johnsson, 2017 and Rootzén & Johnsson, 2016 exploring chemical and oil refining industries were not found. Furthermore, studies, where the implementation of CCS on multiple industries to produce a common final product, were not found. Besides, studies, where the $CO_2$ emissions reduction along the value chain to produce the end-product were assessed, were not found. Finally, studies, where the CCS cost were allocated into multiple products produced by the same industry, were not found.

The knowledge gaps are:

- Allocation of cost impact as well as the $CO_2$ emission reduction at each transformation stage (i.e., from industrial products supply to a product consumed by a final user)
- Effect of bringing forward the CCS implementation costs in the end product

## 1.4 RESEARCH OBJECTIVE

The purpose of this study is to evaluate to what extend CCS implementation in industrial sectors (e.g., cement, steel, petrochemical, and petroleum refining). Additionally, this study aims to assess the product cost impact on final consumers (i.e., people rather than a company or industry). For instance, people do not consume cement directly, rather, they do either through a bridge (i.e., driving way to the office) or purchasing a house in which materials derived from cement are used for its construction. Several products (i.e., consumed directly by people) are selected to be assessed in this study. The selection of these products is based on; raw materials (i.e., derived from energy-intensive industries) used in its production, and the main applications of energy-intensive industries products (i.e., cement used as material for infrastructure and buildings construction).

As a result of the literature review and the knowledge gaps the research question is proposed:

***To what extent does CCS implementation in primary production translates the cost and the $CO_2$ emission reduction across the industry value chain from industrial production to the final product?***

To answer the research question, the following sub-questions are formulated:

- *$Q_1$: What are the key technical factors that influence final product costs and their $CO_2$ emission reduction when CCS is implemented in the production of industrial products?*
- *$Q_2$: To what extent do cost allocation approaches impact the CCS cost across the value chain?*

# 2. METHODOLOGY

This study aims to assess to what extend CCS application in energy-intensive industries (e.g., cement, steel, chemicals, and oil refining) would impact production costs through their value chain. The analysis is done based on a comparative assessment of products derived from industrial processes with and without CCS implementation. In this context, a value chain is composed of three main elements; primary product, intermediate product, and final product. A primary product (e.g., cement) is derived from an energy-intensive production process. In this thesis, CCS is implemented in this part of the value chain. In general, a primary product has little applications on its own. Hence, it is used as a material, together with other materials, to produce an intermediate product (i.e., cement is used to produce concrete). Last, the final product provides a final service to consumers (e.g., bridge). The selection of these products is based on; raw materials (i.e., derived from energy-intensive industries) used in its production, and the main applications of energy-intensive industries products (i.e., cement used as material for infrastructure and buildings construction).

The methodology is divided into three phases; definition, estimation, and assessment. The three phases are interconnected and are presented in *Figure 2-1*.

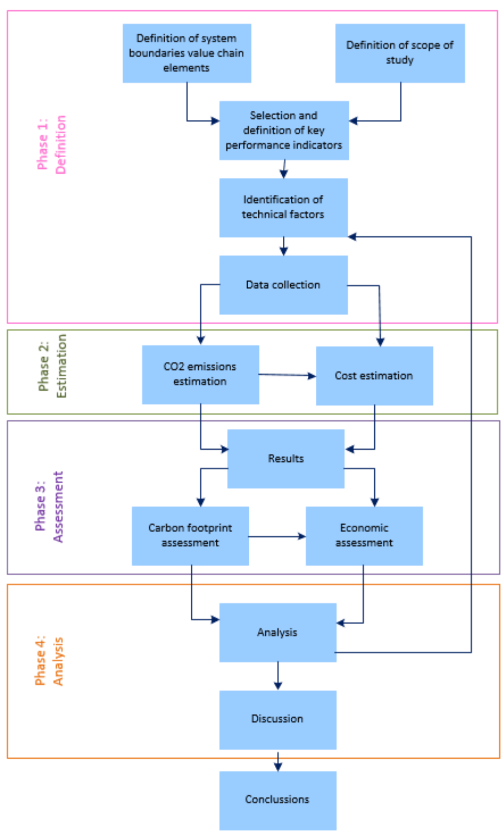



*Figure 2-1 General description of the methodology for the comparative assessment between production costs and CO2 emissions with and without CCS implementation.*

## 2.1 PHASE 1: DEFINITION

The mains steps in phase 1 are; (1) definition of system boundaries and value chain, (2) scoping of the study, (3) selection and description of the key performance indicators, (4) identification of the technical factors, and (5) data collection.

### 2.1.1 SYSTEM BOUNDARIES AND VALUE CHAINS

Defining the system's boundaries has two purposes: (1) defining and categorizing the different products that sequentially shape the value chain; and (2) delimiting the $CO_2$ emissions considered to perform the carbon footprint assessment.

The system boundaries correspond to the aggregation of the three products in an extended gate-to-gate analysis (i.e., primary production gate to final production gate). This means the extraction of raw materials and delivery to production facilities have been excluded from the analysis as well as final product distribution, commercialization, usage, and final disposal. Regarding emissions boundaries, indirect emissions (i.e., due to electricity imported from the grid, heat, and steam produced outside of the production facilities) have been excluded from the analysis as the producer is not responsible for the release of those emissions. Emissions from the extraction of raw materials and emissions related to the final product are excluded (i.e., primary production gate to final production gate). Emissions from transport between primary production facilities to intermediate and/or final product manufacturers are included in the system to account for the emissions of the entire value chain. Figure 2-2 presents the components of the value chain and system boundaries.

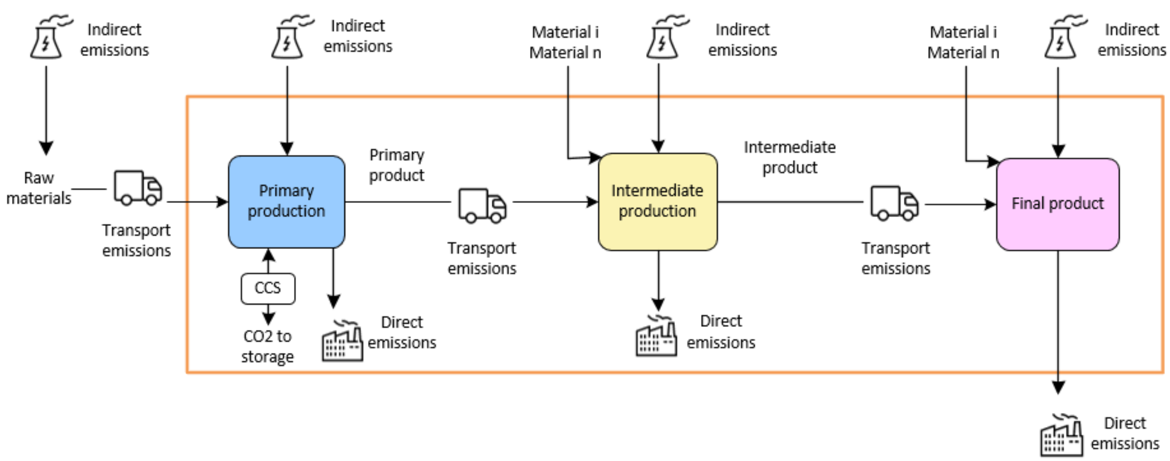



*Figure 2-2 Value chain components and system boundaries*

In this study, several products are studied, therefore each product owns a value chain. Each value chain is assessed in a different case study. The case studies are named base on the final product of each value chain.

This study is conducted through three case studies. The first case study evaluated a value chain related to the construction sector (e.g., transport infrastructure). A bridge represents an example of infrastructure in which both cement and steel are used as a construction material. As there are several types of bridge, a specific type of bridge is used as the case study. Beam bridge is the most frequent type of bridge in Europe (SeRoN, 2011). Thus, a beam bridge is used as a product consumed by final consumers. The second case study evaluated a value chain related to the crop sector in which fertilizers (e.g., nitrogen fertilizers) are consumed. A corn crop represents an example in which ammonia (i.e., chemical industry product) is used to produce fertilizer (e.g., granulated urea). The third case study evaluated a value chain related to the oil refining sector and the industry of polymers. A foam mattress represents an example of the use of plastics in everyday objects in which propylene (i.e., oil refinery product) is used to produce foam to be used as a material in a mattress.

#### 2.1.1.1 CASE STUDY I: BRIDGE

In this case study, the final product is a beam bridge, to be more specific, the Lake Pontchartrain Causeway is located in Louisiana, United States. Although this study is focused on industries in Europe, it is not relevant where the bridge is located as it represents an example of infrastructure. The Lake Pontchartrain is the longest beam bridge in operation nowadays, thus, it is a representative example in which a large amount of construction material was required. Concrete, steel, brick, and composite are the main materials used for common bridge construction (SeRoN, 2011). As brick and composite do not significantly contribute to total material use (around 2% to 3%) (SeRoN, 2011), they are disregarded and only concrete and steel are assumed to be the only construction materials. It is worth mentioning that concrete (derived from cement), and steel are produced in different energy-intensive industries. Therefore, in this case, study there is two value with a common final product (e.g., beam bridge).

##### 2.1.1.1.1 CEMENT VALUE CHAIN

The products that form the cement value chain are; cement as a primary product, concrete as an intermediate product, and a beam bridge (i.e., the Lake Pontchartrain Causeway) as the final product. CCS is implemented in primary production (e.g., cement production). The cement value chain is presented in Figure 2-3. It starts with the processing of raw materials (e.g., limestone, clay, and sandstone) in a cement plant to produce cement. A detailed description of the process is presented in the appendix. Cement is delivered by truck to the concrete production facility and the bridge construction site.

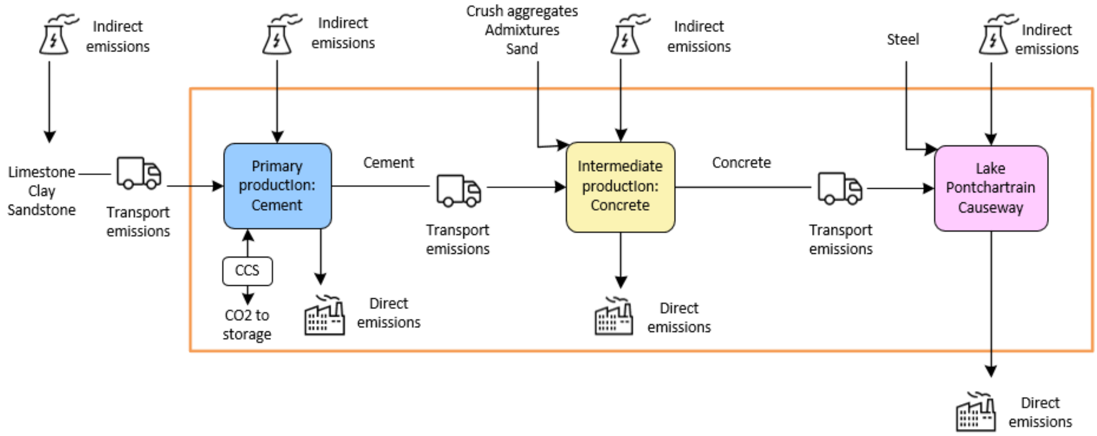



*Figure 2-3 Cement value chain and system boundaries*

### 2.1.1.1.2 STEEL VALUE CHAIN

The products that form the steel value chain are; steel (e.g., hot rolled coil) in several product categories (e.g., wire, rod, and structural steel) as the primary product and a beam bridge (i.e., the Lake Pontchartrain Causeway) as the final product. CCS is implemented in primary production (e.g., steel production). The steel value chain is presented in Figure 2-4. It starts with the processing of raw materials (e.g., iron ore, coke, and limestone) in a steel plant to produce Hot Rolled Coil (HRC). A detailed description of the process is presented in the appendix. HRC can be used as a construction material. However, some extra finishing tasks (e.g., cutting) to produce different product categories (e.g., wire, rods, and structural steel) are required. It is assumed HRC production and finishing tasks are performed in the same facility. Because of this and due to no extra materials are required to produce different steel categories, the intermediate product is non-existent in this value chain. Steel is delivered by truck to the construction site.

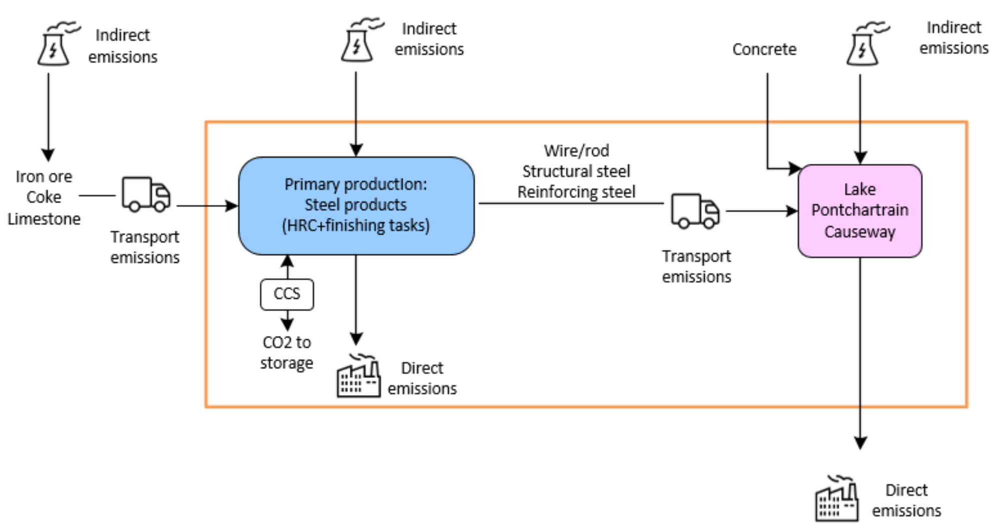



*Figure 2-4 Steel value chain and system boundaries*

The value chain for the bridge case study (i.e., cement and steel value chains together) is presented in Figure 2-5.

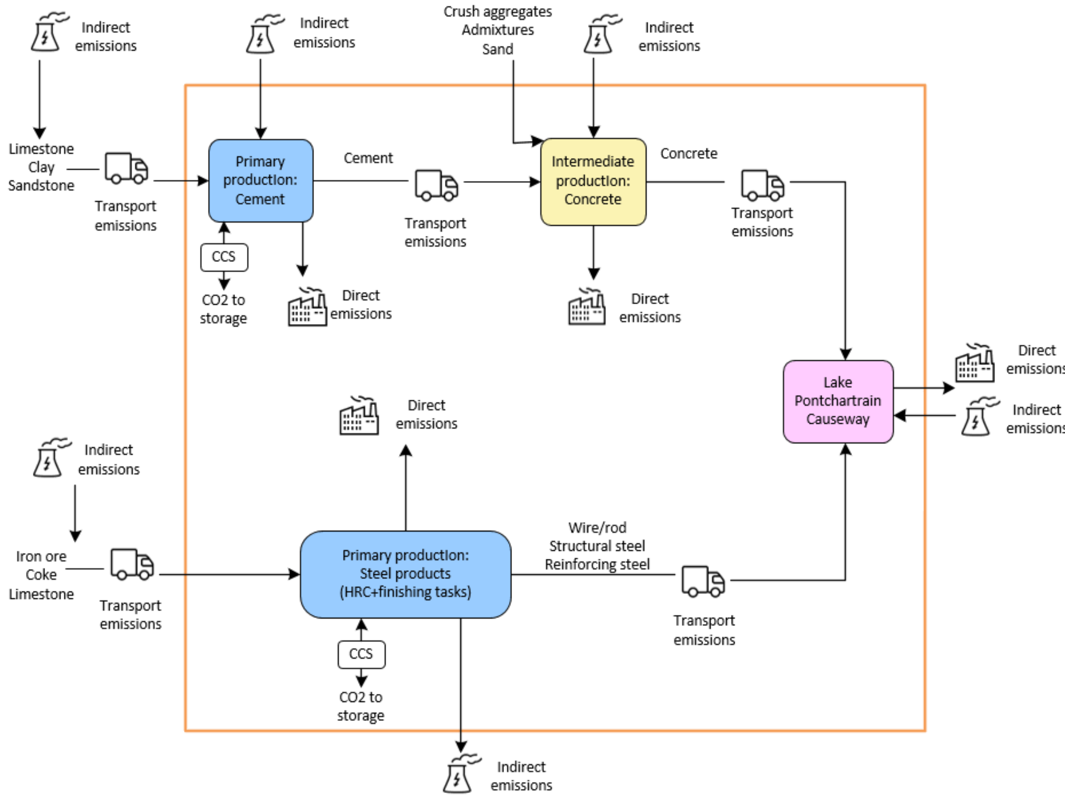



*Figure 2-5 Value chain for case study I: bridge*

### 2.1.1.2 CASE STUDY II: CORN

#### 2.1.1.2.1 CORN VALUE CHAIN

In this case study, the final product is corn. Seeds and fertilizer are the main materials used to grow corn. Fertilizers are produced by the chemical industry (e.g., ammonia and urea production). The products that form the corn value chain are; ammonia as a primary product, urea as an intermediate product, and bulk corn as the final product. CCS is implemented in primary production (e.g., ammonia production). The ammonia value chain is presented in Figure 2-6. It starts with the processing of raw materials (e.g., natural gas and air) in an ammonia synthesis plant to produce ammonia ($NH_3$). A detailed description of the process is presented in the appendix. It is worth mentioning that $CO_2$ removal is inherent to ammonia synthesis (i.e., not related to CCS for mitigation purposes). As ammonia and $CO_2$ are used as feedstock to produce urea, it is assumed urea production is integrated with ammonia plant which is a common practice. Then, granulated urea (i.e., used as a nitrogen fertilizer) is sold to farmers and delivered by truck to the crop site.

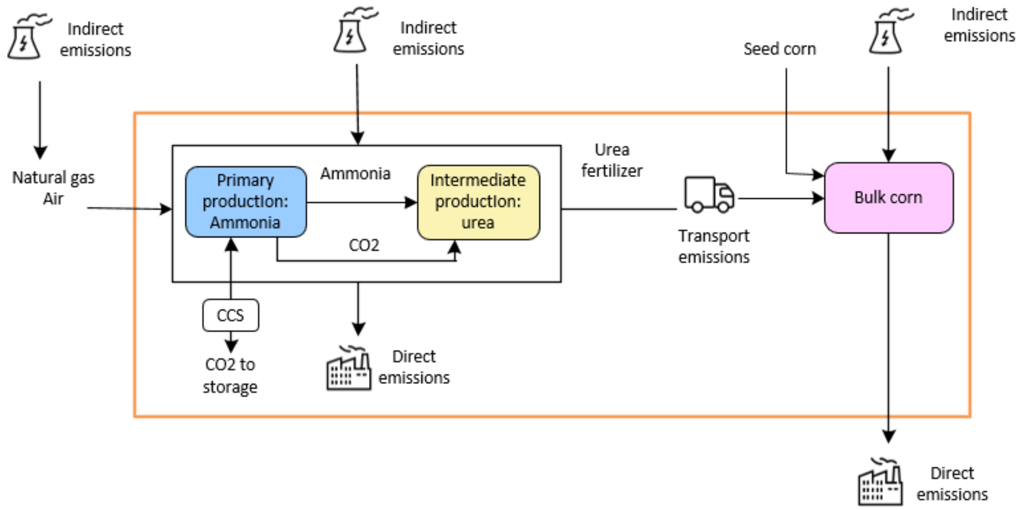



*Figure 2-6 Value chain for case study II: corn*

### 2.1.1.3 CASE STUDY III: MATTRESS

In this case study, the final product is a mattress, to be more specific a queen mattress. Foam and fabric are the main materials used to produce a mattress. The products that form the mattress value chain are; propylene as a primary product, propylene oxide, polyol, and foam as intermediate products, and a mattress as the final product. CCS is implemented in primary production (e.g., propylene production). The mattress value chain is presented in Figure 2-7. It starts with the processing of raw materials (e.g., crude) in an oil refinery plant to produce propylene. A detailed description of the process is presented in the appendix.  Foam is sold to matters of manufacturers. Due to the nature of the materials transport from one producer to another is not considered in this case study.

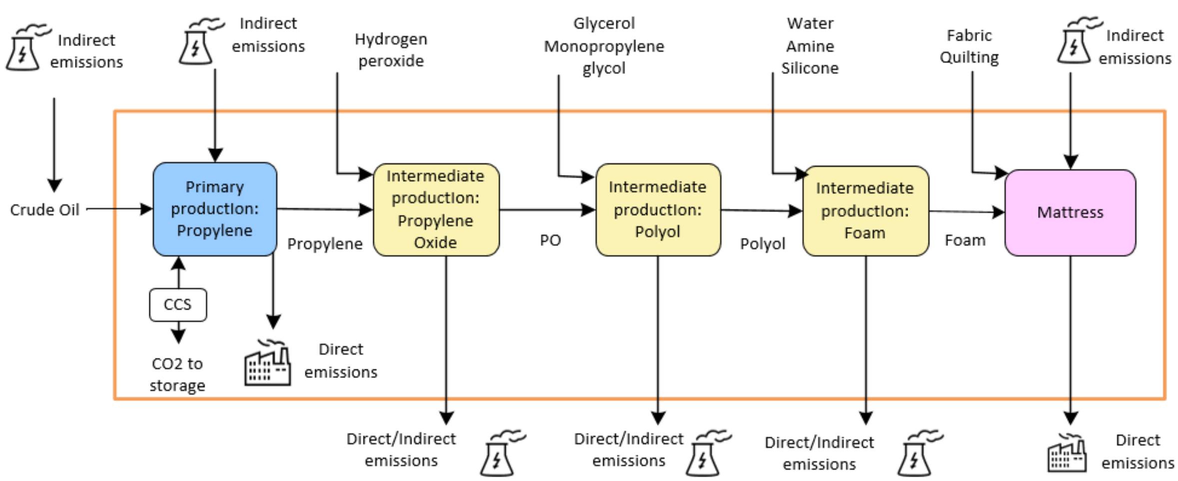



*Figure 2-7 Value chain for case study III: mattress*

### 2.1.2 SCOPING

$CO_2$ emissions related to primary production are estimated under scope 1 classification by the Greenhouse Gas (GHG) Protocol (reference). Scope 1 emissions are direct emissions that a production facility is responsible for. Direct emissions include energy-related emissions from the combustion of fossil fuel and process emissions, other than combustion, that are inherent to the production process (e.g., chemical reactions) (IEA,2019a). Purchased electricity, heat, and steam produced outside of the production plant are excluded from direct emissions. $CO_2$ emissions related to transport (i.e., from primary production facilities to intermediate/final product production facilities) are included in the $CO_2$ accounting. On-site transport emissions (i.e., material transfer within the production facilities) are excluded. $CO_2$ emissions related to final production (e.g., construction emissions, tractor emissions used in farming) and usage are excluded.

Production cost estimation consists of capital cost (CAPEX) and operating costs (OPEX). CAPEX is expressed in terms of total requirement cost (TRC) (e.g., equipment cost, direct costs, contingencies and fees, and owner's costs) (IEAGHG, 2013a). Fixed OPEX includes maintenance, labor costs, and administrative costs. Variable OPEX includes raw material costs and utilities such as electricity and fuel costs (IEAGHG, 2013a). Electricity (i.e., for non-households), natural gas, and diesel 2018 prices in the Netherlands are used for variable OPEX estimation. It is assumed steam is generated on-site by a boiler (e.g., in the steel plant) or waste heat (e.g., in the ammonia synthesis and cement process). $CO_2$ compression is assumed to occur within the production facilities; hence, this cost is included in the $CO_2$ capture cost. $CO_2$ capture cost and $CO_2$ transport and storage cost are included as variable OPEX. Investment costs of the capture and compression units are included as CAPEX. Break-even costs are estimated as part of the economic assessment, hence, profits are excluded. Carbon pricing is excluded in the variable OPEX estimation; however, it is assessed in the sensitivity analysis of production cost. Delivery costs (i.e., from primary production facilities to intermediate or final production facilities) are included. Interest, inflation and depreciation are excluded for production cost estimation and transport cost estimation. All costs are expressed in $€_{2018}$ using the Chemical Engineering Plant Cost Index (CEPCI).

### 2.1.3 KEY PERFORMANCE INDICATORS

Key performance indicators (KPIs) are selected to assess CCS impact on production cost (i.e., in the economic assessment) and impact on $CO_2$ emissions (i.e., in the carbon footprint assessment) in the three elements of the value chain. The KPIs are described below.

#### 2.1.3.1 CARBON FOOTPRINT INDICATORS

a. Specific $CO_2$ emissions are defined as the amount of direct emissions generated on-site and released to the environment (IPCC, 2005b) expressed as a tonne of $CO_2$ per tonne of product ($t_{CO2}/t_{product}$).

b. $CO_2$ capture ratio (CCR) is defined as the $CO_2$ captured divided by the CO2 emitted (Voldsund et al., 2018). It is expressed as:

$$CCR = \frac{CO2_{cap}}{CO2_{gen}}$$

where:

$CO_{2\ cap}$ is the amount of specific direct emissions removed by the capture unit ($t_{CO2}/t_{product}$).

$CO_{2\ gen}$ is the specific direct emissions generated on-site ($t_{CO2}/t_{product}$). In the plant with capture, these emissions include the $CO_2$ generated by fuel combustion during the capture process.

c. $CO_2$ avoided (AC) estimates the direct $CO_2$ emission reductions, referred to CCS, expressed as a tonne of $CO_2$ per tonne of product ($t_{CO2}/t_{product}$). It compares the $CO_2$ emissions of the plant with and without CCS (IPCC, 2005b). It is defined as:

$$AC = \frac{CO_{2_{ref}} - CO_{2_{CCS}}}{CO_{2_{ref}}}$$

where:

$CO_{2\ ref}$ is the specific direct emissions generated on-site, from the plant without CCS, and released to the environment ($t_{CO2}/t_{product}$).

$CO_{2\ CCS}$ is the specific direct emissions generated on-site, from the plant with capture, and released to the environment ($t_{CO2}/t_{product}$).

### 2.1.3.2 ECONOMIC INDICATORS

a. Production cost (PC) is estimated by summing annualized capital cost (CAPEX) and annualized operating cost (OPEX) expressed per tonne of product (€/$t_{ptoduct}$). OPEX is categorized into; variable OPEX (i.e., including fuel cost, raw material costs, and electricity cost), and fixed OPEX (i.e., including operating, labor, and maintenance cost). It is defined as:

$$PC = Annualized\ CAPEX + variable\ OPEX + fixed\ OPEX$$

This indicator is calculated by annualized CAPEX (i.e, based on the plant lifetime expressed in years and an interest rate), annualized variable OPEX, and annualized fixed OPEX costs (IEAGHG, 2013b).

b. $CO_2$ avoided cost (CAC) represents the reduction cost of $CO_2$ emissions (i.e., relative to the production of a tonne of product) by one unit while producing the same amount of output as in a plant without CCS (IPCC, 2005a). It is defined as:

$$CAC = \frac{PC_{CCS} - PC_{ref}}{CO_{2_{ref}} - CO_{2_{CCS}}}$$

Where:
*CAC* is the $CO_2$ avoided cost (€/$t_{CO2}$).
$PC_{CCS}$ is the production cost with CCS (€/$t_{product}$).
$PC_{ref}$ is the production cost without CCS (€/$t_{product}$).
$CO_{2\ ref}$ is the specific direct emissions generated on-site, from the plant without CCS, and released to the environment ($t_{CO2}$/$t_{product}$).
$CO_{2\ CCS}$ is the specific direct emissions generated on-site, from the plant with capture, and released to the environment ($t_{CO2}$/$t_{product}$).

c. $CO_2$ capture cost (CCC) is based on the amount of $CO_2$ captured (IPCC, 2005a) relative to the production of a tonne of product. It is defined as:

$$CCC = \frac{PC_{C} - PC_{ref}}{CO_{2_{captured}}}$$

Where:
*CCC* is the $CO_2$ capture cost (€/$t_{CO2}$).
$PC_{CCS}$ is the production cost with CCS (€/$t_{product}$).
$PC_{ref}$ is the production cost without CCS (€/$t_{product}$).
$CO_{2\ capture}$ is the amount of captured $CO_2$ ($t_{CO2}$/$t_{product}$).

It should be noted the amount of $CO_2$ avoided is less than the amount of $CO_2$ captured (i.e., capture and storage require energy and generate emissions). Therefore, the $CO_2$ avoided cost is higher than the $CO_2$ captured cost (IPCC, 2005a).

### 2.1.4 TECHNICAL FACTORS

In this section, the technical factors required to estimate the key performance indicators are identified and described. Identifying technical factors is useful to determine data collection.

The estimation of the $CO_2$ emission indicators is based on certain factors or characteristics such as production capacity, type of production process, type of fuel (e.g., natural gas, coal), and electricity (i.e., generated on-site or imported from the grid. It is important to determine if the electricity is generated on-site (i.e., by a power plant within the production plant) or if it is imported from the grid. If it is generated on-site, the emissions are considered direct emissions, if not, the emissions are considered indirect emissions and are excluded from the analysis.

Defining the type of process is needed to determine the emission sources (e.g., flue gas emitted in a single stack or multiple stacks) and, in turn, the points of capture. Therefore, along with the capture rate (i.e., percentage of $CO_2$ that can be captured from a stream), and the composition of the flue gas stream the $CO_2$ captured can be known. It should be noted that, when heat waste is not available, the capture unit consumes fuel generating more $CO_2$emissions. Although it is generally not done these emissions can be captured. Finally, the $CO_2$ captured and the $CO_2$ emitted is required to know the $CO_2$ avoided.

The estimation of the economic indicators is based on similar factors as $CO_2$ emission indicators. For instance, the size of the plant (e.g., production capacity) and the equipment cost (i.e., depends on the type of process) determine the capital cost. The type of process and production capacity determine the raw materials and the fuel and electricity consumption, and therefore, the operating costs. Based on the capture technology and the amount of $CO_2$ captured, the $CO_2$ capture cost is known, as well as the $CO_2$ avoided cost.

Summarizing, the technical factors required to estimate KPIs are production capacity, type of process, type of fuel (e.g., coal, natural gas), fuel consumption, electricity consumption (i.e., either if it is imported from the grid or generated on-site), capture technology and its capture rate.

Several factors are affecting the value chain, and thus, impacting cost throughout the value chain. For instance, if primary and intermediate productions are done in the same plant (i.e., steel and ammonia/urea plants) or by different producers (i.e., cement and concrete production.

### 2.1.5 DATA COLLECTION

Data required for KPIs estimation are gathered from literature, previous studies, and research. The main data source to define the reference plant are reports from the IEAGHG (IEA Greenhouse Gas R&D Programme).

## 2.2 PHASE 2: ESTIMATION

There are two scenarios in the case studies; the base scenario without CCS and the CCS scenario where CCS is implemented in the primary production. The main steps in phase 2 are; (1) $CO_2$ emissions estimation, (2) cost estimation, and (3) cost allocation.

### 2.2.1 $CO_2$ EMISSIONS ESTIMATION

This section provides an overview of the direct $CO_2$ emissions along the value chain. The $CO_2$ emissions (with and without CCS) are estimated sequentially at each stage of the value chain as follows: (1) estimating direct $CO_2$ emissions in primary production, (2) estimating direct $CO_2$ emissions in intermediate production, and (3) estimating transport emissions. All $CO_2$ emissions are expressed per tonne of product (i.e., as $t_{CO2}/t_{product}$), except in oil refinery in which annual emissions are reported.

### 2.2.1.1 $CO_2$ EMISSIONS IN PRIMARY PRODUCTION

Direct $CO_2$ emissions for the base scenario (without CCS), in primary production, are estimated as follows:

1. Identifying the $CO_2$ emissions sources; emissions from fuel combustion, process emissions (e.g., chemical reactions), power plant (i.e., in steel plan and oil refinery the electricity is generated on-site), and flue gas emitted from a single or multiple stacks.

2. Estimating the specific $CO_2$ emitted relative to product expressed as $t_{CO2}/t_{product}$. The emissions are reported in the literature in three different ways; (a) $CO_2$ per tonne of product (e.g., in cement, steel, and ammonia/urea production), in this case, no further estimation is needed; (b) flowrate expressed as $tCO_2/h$ (e.g., ammonia/urea production) and (c) annual emissions (e.g., in an oil refinery).

   If emissions are reported as flowrate, they are divided by the product flow rate.

   $CO_2$ emitted during cement production is reported per tonne of clinker. Those emissions are multiplied by a clinker/cement factor to express the $CO_2$ emissions per tonne of cement. Emissions from the oil refinery (i.e., propylene production) are reported as annual emissions.

   In propylene production, the $CO_2$ emissions are reported as $CO_2$ generated in the oil refinery annually. The emissions are estimated as follows:

   Estimate the share of mass content (SMC): the ratio between the propylene annual production and the total products: $SMC = \frac{mpropylene}{\sum_{i=1}^{np} mi}$

   Multiply the annual $CO_2$ emissions by SMC, and divide by the annual production of propylene as follows: $CO2\ emissions = \frac{SMC * \frac{kt_{CO2}}{y}}{\frac{kt_{propylene}}{y}}$

Direct $CO_2$ emissions for the CCS scenario in primary production are estimated as follows:

1. Identifying the $CO_2$ emissions sources; emissions from fuel combustion, process emissions (e.g., chemical reactions), power plant (i.e., in steel plan and oil refinery the electricity is generated on-site), and flue gas emitted from a single or multiple stack.

2. Estimating the amount of $CO_2$ captured relative to product expressed as $t_{CO2}/t_{product}$. The $CO_2$ captured emissions are reported in the literature in two different ways; (a) flowrate expressed as $tCO_2/h$ (e.g., in cement production and ammonia/urea production), and (b) annual emissions (e.g., in an oil refinery).

   If emissions are reported as flowrate, it is divided by the product flow rate.

   In steel production $CO_2$ captured is not reported in the literature. Data given are $CO_2$ emitted before and after capture per source of emissions (e.g., coke oven flue gas, hot stove flue gas) expressed as $tCO_2$/t HRC. Therefore, $CO_2$ captured is determined by the sum of the differences between $CO_2$ emitted before and after $CO_2$ capture.

It should be noted $CO_2$ captured can be also estimated based on the capture rate. For instance, multiplying the amount of $CO_2$ emitted (e.g., from flue gas stack) by the capture rate (i.e., percentage of $CO_2$ that can be captured from a stream).

3. Estimating the $CO_2$ avoided (see section 2.1.3.1)

### 2.2.1.2 $CO_2$ EMISSIONS IN INTERMEDIATE PRODUCTION

In concrete production, the process is driven by electricity (Colangelo et al., 2018). It is assumed electricity is imported from the grid; thus, direct $CO_2$ emissions are non-existent.

Regarding steel, HRC is converted into several products and forms of steel (e.g., wire, rod, and structural steel) utilizing some finishing tasks performed in the same steel mill plant. Those tasks generate $CO_2$ (i.e., additionally to HRC production emissions) (Rootzén & Johnsson, 2016). Therefore, those emissions are added to the $CO_2$ emitted by the production of HRC as following:

$$CO2_{steel} = CO2_{HRC} * q + CO2_{steel}$$

Where:

$CO_{2steel}$ is the specific direct emissions of each steel product ($t_{CO2}/t_{steel}$)
$CO_{2HRC}$ is the specific direct emissions of HRC ($t_{CO2}/t_{HRC}$)
q is the amount of steel obtained from one tonne of HRC ($t_{HRC}/t_{steel}$) (i.e., it is assumed one tonne of HRC is converted into one tonne of any steel product)

Direct emissions are not generated in urea production. Since ammonia and urea productions are integrated, the emissions are expressed as specific e

missions per tonne of urea. Those emissions represent the emissions related to the ammonia that is converted to urea (e.g., $0.57t_{NH3}/t_{urea}$).

It is assumed direct $CO_2$ emissions from polyol and foam production are not generated.

### 2.2.1.3 $CO_2$ EMISSIONS DURING TRANSPORT

Transport emissions per delivered product are estimated based on; fuel consumption, fuel emission factor, annual production (e.g., primary and intermediate production), and an assumed distance as following:

$$CO2_{transport} = \frac{d * fc * fef}{q}$$

Where:

$CO_{2transport}$ is the specific emissions during transport ($t_{CO2}/t_{product}$)
d is an assumed distance (km)
fc is fuel consumption (L/km)
fef is fuel emission factor ($t_{CO2}$/L)
q is amount of product (t)

As steel is a market that is traded globally the distance is not assumed. It is estimated based on Rootzén & Johnsson, 2016; the transport cost of steel is estimated to 5-15% of the selling price of steel products. Based on that, the delivery cost is estimated. Then, an iteration using solver function in Excel is performed to find the distance related to that delivery cost. A detailed explanation is provided in section 2.2.2.3 transport cost.

#### 2.2.1.4 $CO_2$ EMISSIONS IN VALUE CHAIN

$CO_2$ emissions in final product (or value chain) are given by; $CO_2$ emissions in primary production, transport emissions (i.e., from primary production gate to intermediate production gate), $CO_2$ emissions in intermediate production (i.e., in this study direct $CO_2$ emissions in intermediate production are non-existence) (see section 2.2.1.2), and transport emissions (i.e., from intermediate production gate to final production gate) all together. Therefore, $CO_2$ emissions related to final product can be also defined as the embedded $CO_2$ emissions along the value chain.

So far, all $CO_2$ emissions (e.g., in primary, intermediate product, and transport) are expressed per tonne of product. In order to estimate the emissions in the final product (or along the value chain) the amount of material required in each production has to be known. For instance, how many cubic meters of concrete are used in the bridge construction, and consequently, tonnes of cement used to produce that amount of concrete. $CO_2$ emissions accounting is estimated as following:

$$CO2\,vc \;=\; \sum\left(q_p \,*\, CO2_p\right) \,+\left(q_p \,*\, CO2_{tp}\right) + (q_i \,*\, CO2_i) + (q_i * \, CO2_{ti})$$

Where:

$CO_{2vc}$ is the embedded $CO_2$ emissions along the value chain ($t_{CO2}$)
$q_p$ is amount of primary product ($t_{product}$)
$CO_{2p}$ is direct emissions of primary product ($t_{CO2}/t_{product}$)
$q_i$ is amount of intermediate product ($t_{product}$)
$CO_{2i}$ is direct emissions of intermediate product ($t_{CO2}/t_{product}$)
$CO_{2tp}$ is transport emissions of primary product ($t_{CO2}/t_{product}$)
$CO_{2ti}$ is transport emissions of intermediate product ($t_{CO2}/t_{product}$)

### 2.2.1.4.1 BRIDGE

$CO_2$ emissions in a bridge are given by the emissions related to the concrete value chain (see section 2.1.1.1.1) and the emissions related to the steel value chain (see section 2.1.1.1.2) together.

$CO_2$ emissions from concrete value chain are estimated as following:

$$CO2\ cvc\ = \sum(q_c\ *\ CO2_c\ ) + (q_c\ \ *\ CO2_{tc}) + (q_{co} *\ CO2_{tco}\ )$$

Where:

$CO_{2cvc}$ is the $CO_2$ related to concrete value chain ($t_{CO2}$)
$q_c$ is amount of cement ($t_{cement}$)
$CO_{2c}$ is direct emissions of cement production ($t_{CO2}$)
$q_{co}$ is amount of concrete ($m^3$)
$CO_{2tc}$ is transport emissions of cement ($t_{CO2}/t_{cement}$)
$CO_{2tco}$ is transport emissions of concrete ($t_{CO2}/m^3_{concrete}$)

$CO_2$ emissions from steel value chain are estimated as following:

$$CO2\ svc\ = \sum\left(q_s\ [t_{steel}]\ *\ CO2_{steel}\left[\frac{t_{CO2}}{t_{steel}}\right]\right) + \left(q_s\ [t_{steel}]\ *\ CO2_{ts}\ \left[\frac{t_{CO2}}{t_{steel}}\right]\right)$$

Where:

$CO_{2svc}$ is the $CO_2$ related to steel value chain ($t_{CO2}$)
$q_s$ is amount of steel ($t_{steel}$) (i.e., any product category of steel)
$CO_{2steel}$ is direct emissions of steel product ($t_{CO2}/t_{steel}$)
$CO_{2ts}$ is transport emissions of steel ($t_{CO2}/t_{steel}$)

Therefore, the $CO_2$ emitted along the value chain from primary production gate to final production gate (e.g., construction site) is accounted as following:

$$CO2\ bridge\ =\ \ CO2\ cvc + CO2\ svc$$

Where:

$CO_{2bridge}$ is $CO_2$ emissions along the value chain ($t_{CO2}$)
$CO_{2cvc}$ is the $CO_2$ related to concrete value chain ($t_{CO2}$)
$CO_{2svc}$ is the $CO_2$ related to steel value chain ($t_{CO2}$)

### 2.2.1.4.2 CORN

$CO_2$ emissions related to the materials required for corn growing (i.e., emissions along the value chain) are given as follows:

$$CO2\ emissions\ corn\ \ = \sum(q_u\ \ *\ CO2_u\ ) + (q_u\ *\ CO2_{tu}\ \ )$$

Where:
*$CO_2$ emissions corn* is the $CO_2$ emissions along the value chain ($t_{CO2}$/acre)

$CO_{2u}$ is direct emissions of urea production ($t_{CO2}/t_{urea}$). These emissions include the emissions related to ammonia synthesis.
$q_u$ is the amount of urea used as fertilizer per acre ($t_{CO2}$/acre)
$CO_{2tu}$ is emissions during transport ($t_{CO2}/t_{urea}$)

##### 2.2.1.4.3 MATTRESS

$CO_2$ emissions related to the materials required to produce a mattress (i.e., emissions along the value chain) are given as follows:

$$CO2\ emissions\ mattress\ =\ CO2_{propylene} * q1 * q2 * q3$$

Where:
$CO_2$ emissions mattress is the $CO_2$ emissions along the value chain ($kg_{CO2}$/mattress)
$CO2_{propylene}$ is direct emissions of propylene production ($kg_{CO2}/kg_{propylene}$)
$q_1$ is the amount of propylene required to produce 1 kg of polyol ($kg_{propylene}/kg_{polyol}$)
$q_2$ is the amount of polyol required to produce 1 kg of foam ($kg_{polyol}/kg_{foam}$)
$q_3$ is the amount of foam to produce a mattress ($kg_{foam}$/mattress)

### 2.2.2 COST ESTIMATION

This section provides an overview of the cost estimation along the value chain. The $CO_2$ emissions (with and without CCS) are estimated sequentially at each stage of the value chain as following: (1) estimating primary production cost, (2) estimating intermediate production cost, (3) estimating transport costs, and (4) estimating final production cost. All costs are expressed per tonne of product (i.e., as $€_{2018}/_{product}$). If cost data in literature are expressed in a different currency (e.g., dollars) first it is converted to euro, then updated to 2018 (e.g., in steel production).

#### 2.2.2.1 PRIMARY PRODUCTION COST

Break-even cost in primary production in the reference scenario (without CCS) is estimated as following:

1. Estimating fuel consumption (e.g., coal and natural gas) per tonne of product. Fuel consumption is reported in literature in different ways; (a) coal flow rate expressed as t/h (e.g., in cement production) and (b) natural gas expressed as $GJ/t_{product}$ (e.g., steel production and urea production). In this case no further estimation is needed.

   If coal flow rate is expressed as flow rate it is divided by the product flow rate as following:

$$coal\ consumption\ \left[\frac{t_{coal}}{t_{product}}\right] = \frac{t_{coal}}{h} \div \frac{t_{product}}{h}$$

2. Estimating fuel cost (e.g., coal and natural gas) per tonne of product based on fuel consumption and costs for coal and natural gas in 2018 as following:

$$coal\ cost\ \left[\frac{€}{t_{product}}\right] = coal\ consumption\ \left[\frac{t_{coal}}{t_{product}}\right] * coal\ cost\ \left[\frac{€}{t_{coal}}\right]$$

$$natural\ gas\ cost\ \left[\frac{€}{t_{product}}\right] = natural\ gas\ consumption\ \left[\frac{GJ}{t_{product}}\right] * natural\ gas\ cost\ \left[\frac{€}{GJ}\right]$$

It is assumed steam is generated on-site by a boiler (e.g., in the steel plant) or waste heat (e.g., in the ammonia synthesis and cement process).

In the oil refinery (i.e., propylene production) the natural gas cost is estimated as annual cost rather than per tonne of product. In literature the natural gas consumption is given per annual consumption.

$$natural\ gas\ cost\ \left[\frac{€}{annual}\right] = natural\ gas\ consumption\ \left[\frac{GJ}{annual}\right] * natural\ gas\ cost\ \left[\frac{€}{GJ}\right]$$

3. 3. Estimating electricity consumption per tonne of product based on electricity consumption and cost for electricity in 2018 as following:

$$electricity\ cost\ \left[\frac{€}{t_{product}}\right] = electricity\ consumption\ \left[\frac{kWh}{t_{product}}\right] * electricity\ cost\ \left[\frac{€}{kWh}\right]$$

4. Estimating raw materials cost and other consumables per tonne of product. In literature the materials cost for cement and steel production are reported per tonne of product. Those costs are updated to 2018 using the Chemical Engineering Plant Cost Index (CEPCI) as following:

$$Cost_{2018} = Cost_i * \frac{CEPCI_{2018}}{CEPCI_i}$$

Where:
$cost_i$ represents the cost given in literature at year i
$CEPCI_i$ represents the index at year i.

It should be noted step 1 and 2 are also performed to estimate some raw materials consumption and its cost. For instance, in steel and ammonia production. In steel production, iron ore cost is estimated as following:

$$iron\ ore\ cost\ \left[\frac{€}{t_{HRC}}\right] = \ iron\ ore\ consumption\ \left[\frac{t_{iron\ ore}}{t_{HRC}}\right] * iron\ ore\ cost\ \left[\frac{€}{t_{iron\ ore}}\right]$$

In ammonia production the raw material cost (e.g., natural gas) is estimated as is showed in step 2.

In the oil refinery (i.e., propylene production) the cost of crude oil is excluded.

5. Estimating variable OPEX expressed as €/$t_{product}$ by summing fuel cost, electricity cost, and raw material cost as following:

$$Variable\ OPEX\ \left[\frac{€}{t_{product}}\right] = fuel\ cost\ \left[\frac{€}{t_{product}}\right] + electricity\ cost\ \left[\frac{€}{t_{product}}\right] + \ raw\ material\ cost\ \left[\frac{€}{t_{product}}\right]$$

6. Estimating fixed OPEX expressed as €/$t_{product}$. In literature labour and maintenance cost for cement, steel and ammonia/urea production are reported per tonne of product. Those costs are updated to 2018 using the Chemical Engineering Plant Cost Index (CEPCI) (see step 4).

7. Estimating CAPEX expressed as €/$t_{product}$. Costs are reported in literature in three ways; (a) capital cost expressed as €/t $_{product}$, (b) annualized capital cost, and (c) total capital requirement (TCR). TCR is the capital investment (CAPEX) that includes equipment cost, direct costs, contingencies and fees, and owner's costs

   If capital cost is expressed per tonne of product (i.e., data from literature), the cost is updated to 2018 using CEPCI (see step 4). If annualized CAPEX is reported, the cost is divided by the annual production and then updated to 2018 using CEPCI.

   Annualizing CAPEX as following:

$$Annualized\ CAPEX\ \left({}^{€}/_{y}\right) = CAPEX\ (€) * \frac{i}{1 - \frac{1}{(1+i)^t}}$$

   where $i$ is the interest rate and $t$ is the plant lifetime expressed in years. The annualized CAPEX is divided by the annual production and, then, updated to 2018 using CEPCI

8. Estimating production cost (PC) by summing variable OPEX, fixed OPEX and CAPEX as following:

$$PC\ \left[\frac{€}{t_{product}}\right] = varibale\ OPEX\ \left[\frac{€}{t_{product}}\right] + fixed\ OPEX\ \left[\frac{€}{t_{product}}\right] + \ annualized\ CAPEX\ \left[\frac{€}{t_{product}}\right]$$

In literature, data to estimate the production cost of cement is reported per tonne of clinker (i.e., clinker is a cement precursor along the cement production process). A detailed explanation about the cement production process is presented later (see section). In order to estimate the production cost of cement, clinker production cost is multiplied by a clinker/cement factor (Voldsund et al., 2018) as following:

$$PC_{cement}\left[\frac{€}{t_{cement}}\right] = PC_{clk}\left[\frac{€}{t_{clk}}\right] * factor \left[\frac{t_{clk}}{t_{cement}}\right]$$

Since ammonia synthesis and ammonia production are integrated into the same production facilities, data gathered from literature reports the operating cost and capital cost per tonne of urea. This means that the production cost of the ammonia that is converted to urea is included in the urea production cost. A detailed explanation about the ammonia and urea production process is presented later (see section).

In propylene production the production cost Is estimated in a different way. In an oil refinery the cost of crude and the product prices are required to estimate the optimum product yield (IEAGHG, 2017c). However, to estimate the refinery processing cost (i.e., processing cost per oil barrel) the cost of the feedstock (e.g., crude oil and imported vacuum gasoil) is not required (IEAGHG, 2017c). Therefore, the production cost is not expressed per tonne of product (e.g., €/$t_{propylene}$). Instead, the annual refinery processing cost (e.g., annualized CAPEX and annual OPEX) is reported.

In the CCS scenario fuel and electricity consumption increase due to the operation of the capture and compression units. Also, transport and storage cost is included as part of variable cost. There is, also, an increase in fixed costs and CAPEX due to extra labor required for the CCS operation and the investment required for the capture and compression units. Therefore, the estimations for CCS cost are added to the costs in the reference scenario in order to estimate the production cost with CCS implementation in the production process.

Production cost in primary production in the CCS scenario is estimated as following:

9. Estimating fuel consumption related to $CO_2$ capture (e.g., coal and natural gas) per tonne of product (see step 1). Then, add the value to the reference scenario value.

10. Estimating fuel cost related to $CO_2$ capture (e.g., coal and natural gas) per tonne of product based on fuel consumption and prices for coal and natural gas in 2018 (see step 2). Then, add the value to the reference scenario value.

11. Estimating electricity consumption per tonne of product related to $CO_2$ capture (see step). Then, add the value to the reference scenario value.

12. Estimating raw materials cost and other consumables per tonne of product (see step 4). The capture process requires additional materials such as water and waste disposal.

13. Estimating the $CO_2$ transport and storage cost based on the amount of CO2 captured and the transport and storage (e.g., 10 €/$t_{CO2}$) cost as following:

$$CO_2\ transport\ and\ storage\ \left[\frac{€}{t_{product}}\right] = CO_2\ captured\ \left[\frac{t_{CO2}}{t_{product}}\right] * 10\ \left[\frac{€}{t_{CO2}}\right]$$

14. Estimating CCS variable OPEX expressed as €/$t_{product}$ by summing fuel cost, electricity cost, raw material, and $CO_2$ transport and storage cost as following:

$$Variable\ OPEX\ CCS\ \left[\frac{€}{t_{product}}\right] = fuel\ cost\ CCS\ \left[\frac{€}{t_{product}}\right] + electricity\ cost\ CCS\ \left[\frac{€}{t_{product}}\right] + raw\ material\ cost\ \left[\frac{€}{t_{product}}\right] + t\&s\ \left[\frac{€}{t_{product}}\right]$$

15. Estimating fixed OPEX expressed as €/$t_{product}$ related to $CO_2$ capture (see step 6). Then, add the value to the reference scenario value.

16. Estimating CAPEX (i.e., annualized CAPEX divided by annual production) expressed as €/$t_{product}$ related to $CO_2$ capture (see step 7). Then, add the value to the reference scenario value.

17. Estimating production cost for CCS scenario by summing variable OPEX, fixed OPEX and CAPEX as following:

$$PC\ CCS\left[\frac{€}{t_{product}}\right] = varibale\ OPEX\ CCS\ \left[\frac{€}{t_{product}}\right] + fixed\ OPEX\ CCS\left[\frac{€}{t_{product}}\right] + \ annualized\ CAPEX\ CCS\ \left[\frac{€}{t_{product}}\right]$$

##### 2.2.2.1.1 CCS COST ALLOCATION

In cement, steel, and ammonia/urea production the CCS cost is allocated directly to the products since there by -products are non-existence. It should be noted in ammonia/urea production, 100% of ammonia is converted to urea in the CCS scenario. In order to allocate CCS cost in propylene production (e.g., oil refinery) different cost allocation approaches using physical measures are explored.

- Approach 1: mass-based allocation. Costs are allocated to multiple products based on the Share of Mass Content (SMC) defined as the ratio between the total annual production of the product of interest and the total annual oil products product (in tons) (Moretti et al., 2017) as following:

$$SMC = \frac{m_i}{\sum_{i=1}^{np} mi}$$

- Approach 2: energy-based allocation. Costs are allocated to multiple products based on the Share of Energy Content (SEC) defined as the ratio between the total annual production of the product of interest and the total annual oil products (in tons) and its Lower Heating Value (LHW, in MJ/kg) (Moretti et al., 2017) as following:

$$SEC = \frac{m_i LHV_i}{\sum_{i=1}^{np} m_i LHV_i}$$

In approach 1 and approach 2 there are two ways to estimate SMC and SEC respectively.

- 1a and 2a: product streams. SMC and SEC values are estimated based on mass and LHV of the oil product streams (i.e., the output that a refinery produces with a market value such as propylene, gasoline, diesel, etc). This approach aims to allocate the CCS cost considering the oil refining process a black box and only considering the output from the process.

- 1b and 2b: process streams SMC and SEC values are estimated based on mass and LHV of the on the output streams of certain equipment (e.g., crude distillation unit) within the process. This approach aims to allocate the CCS cost in each process streams involved in the product of interest (e.g., propylene).

A detailed explanation of the oil refining process is given in the appendix.

CCS cost using process streams (1b and 2b) is allocated as following and presented in Figure 2-8:

1. Identifying the units from emissions are captured (e.g., power plant, FCC, CDU, VDU, and SMR)
2. Dividing the CCS cost based on its share of total $CO_2$ emitted by the total $CO_2$ emitted annually in the refinery. For instance, $CO_2$ emissions from CDU are divided by the total emission.
3. Multiplying the CCS cost (annualized CAPEX, and annual OPEX) by the share (%) estimated in the previous step.
4. Allocating the CCS cost related to the power plant and CDU into the CDU units. It worth mentioning that power plant cost is allocated to CDU due to CDU is the first unit where the refining process starts.
5. Estimating SMC or SEC based on the process streams (in and out) in the CDU and multiplying by the CCS cost estimated in (4)
6. Allocating the CCS cost related to VDU into the VDU unit and add the cost estimated in (5)
7. Estimating SMC and SEC based on the process streams (in and out) in the VDU and multiplying by the CCS cost estimated in (6)
8. Allocating the CCS cost related to FCC into the FCC unit and add the cost estimated in (7)
9. Estimating SMC and SEC based on the process streams (in and out) in the FCC and multiplying by the CCS cost estimated in (7)
10. The resulting CCS cost for propylene at this point represents the amount the CCS cost that should be allocated to propylene production.

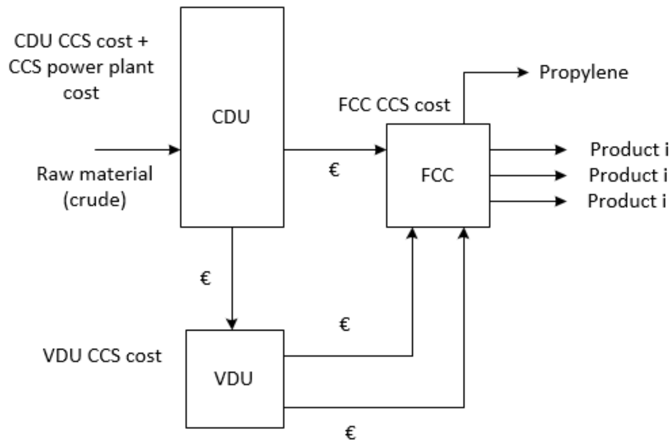



*Figure 2-8 Overview of the process stream approach for SMC and SEC valued.*

### 2.2.2.2 INTERMEDIATE PRODUCTION COST

Concrete production costs consist of variable cost (e.g., raw materials cost and delivery cost), fixed cost, and plant cost (Rootzén & Johnsson, 2017). Raw materials cost (except cement), fixed cost, and plant cost are given in the literature. Cement cost is estimated as part of primary production cost and delivery cost is estimated based on the transport cost (see section 2.2.2.3 transport cost) in which a detailed explanation is provided. It should be noted the difference between the reference scenario and the CCS scenario is given by the cement production cost in both scenarios. Meaning that raw materials cost (excluding cement), fixed cost, and plant cost remain constant in both scenarios.

Concrete cost for reference scenario (without CCS) is estimated as follows:

18. Estimating the cost of each raw materials required to produce a cubic meter of concrete as follows:

$$mc = \sum_{i}^{np} cm * qm$$

Where:
mc is the concrete material cost in (€/$m^3$)
cm is the cost of material (€/ kg)
qm is the amount of material used to produce 1 $m^3$ of concrete (kg/ $m^3$)

It should be noted that the production cost of cement used to estimate concrete material cost comes from the primary production cost in the reference scenario (without CCS) and updated to 2018.

19. Estimating concrete production cost (CC) by summing concrete materials cost, delivery cost, fixed cost and plant cost as following:

$$CC = mc + dc + fc + pc$$

Where
CC is the concrete production cost (€/m$^3$)
$m_c$ is the concrete material cost (€/m$^3$)
$d_c$ is the delivery cost from the concrete plant to the construction site (€/m$^3$)
$f_c$ is the fixed cost of concrete (€/m$^3$)
$p_c$ is the plant cost (€/m$^3$)

20. It should be noted that in literature the material, delivery, plant, and fixed cost are given as a percentage. For instance, material represents 50% of the production cost. Based on that, the production cost value is double the material cost value.

21. Estimating the breakdown of all cost elements. Fixed cost and plant costs are multiplied by its share (%) (i.e., data from literature) in the concrete production cost to determine those costs. Then, add the delivery cost (based on the transport model) and divide it by the construction cost.

To estimate the concrete cost in the CCS scenario, the cement cost with CCS (instead of cement cost in the reference scenario) is used to estimate the concrete material cost. Raw materials cost (excluding cement), fixed cost, and plant cost do not have a change compared to the reference scenario.

Regarding steel, HRC is produced in the steel mill plant. However, HRC is converted into several products and forms of steel (e.g., wire, rod, and structural steel) utilizing some finishing tasks performed on the same site. A relative cost[1] is used to represent the differences in each steel product cost (Rootzén & Johnsson, 2016) as following:

$$Steel\ cost = BEC\ of\ HRC * relative\ cost$$

where:
Steel cost is the production cost of each steel product (€/$t_{steel}$)
BEC of HRC is the production cost of HRC (€/$t_{HRC}$)
relative cost is the ratio of each steel category price (€/$t_{steel}$) and HRC price (€/$t_{HRC}$) in 2018

[1] Relative cost (or price) is a cost (price) in terms of another cost (price) (i.e., ratio of two prices).

Urea production cost is estimated together with the ammonia production since the production facilities are integrated. The cost estimation follows the steps provided in section 2.2.2.1.

Polyol cost for reference scenario (without CCS) is estimated as following:

Estimating the cost of each raw materials required to produce a kg of a polyol as following:

$$pc = \sum_{i}^{np} cm * qm$$

Where:
pc is the polyol material cost in (€/kg)
cm is the cost of material (€/ kg)
qm is the amount of material used to produce 1 kg of polyol (€/kg)

It should be noted that the production cost of propylene used to estimate the polyol material cost should come from the primary production cost in the reference scenario (without CCS). However, since the propylene production cost (€/$t_{propylene}$) is not estimated in this study the commercial price of propylene in 2018 is considered the production cost. It is assumed the increment in the propylene processing cost (i.e., from oil refinery processing cost) is considered the increment in the production cost of propylene.

To estimate the polyol cost in the CCS scenario, the propylene cost with CCS (instead of propylene cost in the reference scenario) is used to estimate the polyol material cost. The cost of the other materials does not have a change compared to the reference scenario.

Foam cost for reference scenario (without CCS) is estimated as follows:

Estimating the cost of each raw materials required to produce a kg of foam as following:

$$fc = \sum_{i}^{np} cm * qm$$

Where:
fc is the foam material cost in (€/kg)
cm is the cost of material (€/ kg)
qm is the amount of material used to produce 1 kg of foam (€/kg)

To estimate the foam cost in the CCS scenario, the polyol cost with CCS (instead of polyol cost in the reference scenario) is used to estimate the foam material cost. The cost of the other materials does not have a change compared to the reference scenario.

### 2.2.2.3 TRANSPORT COST

A road transport model is developed (i.e., adapted from Moncada et al, 2019). It is assumed the transport fleet is owned by each producer (e.g., cement producer). The truck characteristics (e.g., cabin type, truck weight, payload capacity, and fuel consumption per kilometer) and the trip characteristics (e.g., assumed distance, and assumed average speed) are defined. Based on those characteristics, fuel consumption, trips, drivers, and trucks required for the transport model are estimated as follows:

1. Defining the amount of product to be transported annually (i.e., based on primary and intermediate annual production).
2. Estimating the driving time (assumed distance divided by assumed average speed).

$$Driving\ time_{\ one\ way} = \left(distance\ \frac{km}{trip} \div speed\ \frac{km}{h}\right)$$

3. Based on (1), estimating the total number of trips (annual production divided by the payload capacity).

$$Payload\ capacity = \max truck\ weight\ t - kerb\ weight\ t$$

where kerb weight is the unloaded weight (e.g., no cargo and no passengers)

$$Number\ of trips = annual\ production\ \frac{t}{y} \div payload\ capacity\ t$$

4. Based on (2) and (3), estimating the total driving time for all trips.

$$Total\ driving\ time = \left(number\ of\ trips\ * driving\ time \frac{h}{trip}\right)$$

5. Based on (4), estimating the total mileage (total time of trips multiplied by the assumed distance).

$$Mileage = \left(number\ of\ trips\ * distance\ \frac{km}{trip}\right)$$

6. Based on (4), estimating the number of drivers (total driving time divided by full-time employee (FTE) hours in a year.

$$Number\ of\ drivers = total\ driving\ time\ \frac{h}{y} \div FTE\ \frac{h}{y}$$

7. Based on (4), estimating the number of trucks (total driving time divided by hours worked during daily shifts in a year).

$$Number\ of\ trucks = \ total\ driving\ time\ \frac{h}{y}\ \div 5840\ h$$

two shifts per day of 8 hours are assumed during the year (i.e., expressed as 5848h)

8. Based on (5), estimating fuel consumption (total mileage multiplied by fuel consumption per kilometer).

Transport cost estimation is given by CAPEX and OPEX together as follows:

9. Estimating annualized CAPEX based on the total cost of truck (e.g., cabin, trailer, and tires):

$$Annualized\ CAPEX\ \left(\text{€}/y\right) = CAPEX\ (\text{€}) * \frac{i}{1 - \frac{1}{(1+i)^t}}$$

where $i$ is the interest rate and $t$ is the lifetime expressed in years.

10. Estimating OPEX based on fuel price and fixed OPEX (e.g., maintenance and repair, tires, insurance, and labor) based on an investment (CAPEX) shares (i.e., tires cost is estimated as 3% of investment).

11. Estimating transport cost expressed per tonne of a product as follows:

$$Transport\ cost\ \left[\frac{\text{€}}{t_{product}}\right] = \frac{annualized\ OPEX\ [\text{€}] + annualized\ CAPEX\ [\text{€}]}{annual\ production\ of\ product\ \left[t_{product}\right]}$$

Transport costs are kept constant through the assessment for both cases (without CCS with and CCS) and are updated to the year 2018 using the Transport Consumer Price Index (CPI).

#### 2.2.2.4 FINAL PRODUCTION COST

The breakdown of the bridge construction cost is given by four categories; superstructure cost, services & ancillaries, site preparation, and substructure work. The superstructure cost is subcategorized into; the cost of material (i.e., 24% of total construction cost), material manipulation (i.e., concrete placing, assembling of prefabricated elements), and others (Kim et al., 2009). Each category has a share (i.e., expressed ad percentage) of its contribution to the total construction cost. The cost of material is estimated based on steel and concrete production cost.

The bridge construction cost for the reference scenario (without CCS) is estimated as follows:

1. Estimating the material construction cost is given by the amount of steel and concrete used as a construction material as well as its costs as follows:

$$BC = \sum (q_c * CC) + (q_s * SC) + (q_s * d_s)$$

Where

BC is the bridge construction cost (€)

qc is the amount of concrete used in the bridge construction ($m^3$)
CC is the concrete cost (€/$m^3$)
qs is the amount of steel used in the bridge construction (tonne)
SC is the steel cost (€/tonne)
ds is the steel delivery cost form steel plant to construction site (€/tonne)

2. Estimating the superstructure cost based on the material construction cost divided by its percentage of total construction cost. For instance, divided by 24%. Then, estimating the cost for all the elements that compose the superstructure cost multiplying its share of superstructure cost (%) and the superstructure cost.

3. Estimating the total construction cost based on the superstructure cost divided by its percentage of total construction cost.

4. Estimating the services & ancillaries, site preparation, and substructure work cost multiplying the total construction cost and its contribution (%) to the total production cost.

To estimate the bridge construction cost in the CCS scenario, the material cost (e.g., steel and concrete) with CCS is used to estimate the material construction cost. The cost of the other elements remained unchanged.

The breakdown of the operating cost of the corn crop is given by different elements (e.g., fertilizer cost, seed, chemicals, irrigation water, and fuel and electricity) expressed in percentage of the total operating cost. The labor cost has been excluded. The costs are updated to 2018 using the Food Price Index.

The operating cost of crop corn per acre for the reference scenario (with CCS) is estimated as follows:

1. Estimating the fertilizer cost based on the urea cost and the amount of urea required per acre.

2. Estimating the total operating cost based on the fertilizer cost divided by its percentage of total operating cost. Then, estimate the cost for all the elements that compose the operating cost.

To estimate the operating cost of crop corn in the CCS scenario, the fertilizer cost (e.g., urea cost) with CCS is used to estimate the operating cost. The cost of the other elements remained unchanged.

The breakdown of the mattress production cost is given by different elements (e.g., foam cost, outer fabric, quilting, and quilting foam cost) expressed in percentage of the total production cost. The labor cost has been excluded.

The production cost of a queen mattress for the reference scenario (without CCS) is estimated as following:

1. Estimating the foam cost based on the amount of foam required in one mattress and its cost.

2. Estimating the mattress production cost based on the foam cost divided by its percentage of total production cost. Then Then, estimating the cost for all the elements that compose the production cost.

To estimate the mattress production cost CCS scenario, the foam cost with CCS is used to estimate the production cost. The cost of the other elements remained unchanged.

## 2.3 PHASE 3: ASSESSMENT

The main steps in phase 3 are; (1) carbon footprint assessment and (2) economic assessment. The assessment is done based on a comparative analysis of the key performance indicators. The carbon footprint assessment is based on a comparative analysis between the carbon footprint indicators. The economic assessment is based on a comparative analysis between the economic indicators.

## 2.4 PHASE 4: ANALYSIS

In this section, the case studies are analyzed to provide further understanding of the results. Besides, a sensitivity analysis is performed to provide a better understanding of the economic performance indicators when there is uncertainty in fuel cost and $CO_2$ capture technologies investment cost along the time. The variation in the costs is presented as follows:

- Coal cost: +/- 50% of the cost in the reference scenario
- Electricity cost: +/- 50% of the cost in the reference scenario
- Natural gas cost: +/- 50% of the cost in the reference scenario
- CAPEX of $CO_2$ capture technologies: +35/- 15% of the CCS scenario estimate

Finally, a carbon price[2] is included to evaluate the difference in the production cost with and without CCS to evaluate the economic viability of implanting CCS in primary production.

The sub-research questions are answered and discussed in the discussion section. Also, the limitation of this research is discussed. The main research question is answered in the conclusions.

[2] A carbon price of $50/t $CO_2$ (45€$_{218}$/t $CO_2$) is used by some companies for screening projects (IEA, 2018)

# 3. RESULTS

In this section, the results of the $CO_2$ emissions estimation and the economic estimations are presented and compared in the carbon footprint assessment and the economic assessment. Subsequently, the key performance indicators are presented. The key performance indicators are divided into carbon footprint indicators (e.g., $CO_2$ capture ratio and $CO_2$ avoided) and economic indicators (e.g., production cost, $CO_2$ avoided cost and $CO_2$ capture cost).

## 3.1 CASE STUDY I: BRIDGE

### 3.1.1 CEMENT PRODUCTION

The $CO_2$ emissions estimation and cost estimation presented in this section are based on a cement plant with a capacity of 1.36 Mt cement per year through a dry kiln process. Coal is used as fuel and electricity is imported from the grid. In the CCS scenario, integrated oxy-fuel and a tail-end calcium looping (CaL) capture technology are evaluated.

#### 3.1.1.1 CARBON FOOTPRINT ASSESSMENT

In Table 3.1 the direct emissions before and after capture, the $CO_2$ capture, the capture ratio, and the $CO_2$ avoided in each scenario are presented. In the reference scenario (without CCS) direct $CO_2$ emissions are generated from the calciner and the rotatory kiln as a consequence of the combustion of fossil fuels and the limestone calcination process.

*Table 3.1 Direct CO2 emissions of the reference cement plant with and without CCS*

| **$CO_2$ emissions** | **Reference scenario** | **CCS scenario** | |
|---|---|---|---|
| | | **Oxyfuel** | **CaL** |
| $CO_2$ generated (before capture) [a] ($t_{CO2}/t_{cement}$) | 0.63 | 0.65 | 0.91 |
| $CO_2$ captured ($t_{CO2}/t_{cement}$) | | 0.58 | 0.85 |
| $CO_2$ emitted (after capture) ($t_{CO2}/t_{cement}$) | | 0.065 | 0.06 [b] |
| $CO_2$ avoided [c] | | 90% | 91% |
| Cement delivery [d] ($kg_{CO2}/t_{cement}$) | 6.6 | 6.6 | 6.6 |

Emissions from fuel combustion and calcination
[b] Includes emissions from CPU, CaL calciner, and kiln flue gas
[c] Based on $CO_2$ emissions in the reference scenario (without capture)
[d] Based on transport model, from cement plant to concrete production facilities

In terms of emission reductions (e.g., $CO_2$ avoided) both capture technologies achieve similar values. However, there are some differences in terms of electricity and fuel consumption. It is worth mentioning that electricity is imported from the grid (i.e., indirect emissions), therefore, any variation in electricity consumption in the CCS scenarios does not contribute to the $CO_2$ estimation as it is discussed in the methodology (see section 2.1.2).

In the oxyfuel case, there is a slight increase in coal consumption, compared to the reference scenario, due to the modified units for the oxyfuel integration. Therefore, the $CO_2$ generated before capture in the oxyfuel scenario is almost unchanged compared to the reference scenario (see table_). The electricity demand increased by about 110% (from 97 to 207 kWh/$t_{cement}$), mainly due to the air separation unit (ASU) and the $CO_2$ purification unit (CPU) power demand. Electricity is imported from the grid to supply the required electricity.

In the CaL tail-end configuration the demand for coal, compared to the reference scenario, increased about 130% (from 0.11 to 0.26 $t_{coal}/t_{cement}$) due to the fuel consumption in the CaL calciner. Therefore, the $CO_2$ generated before capture increase by about 45% (from 0.63 $t_{CO2}/t_{cement}$ to 0.91 $t_{CO2}/t_{cement}$) compared to the reference scenario (see table_). Those extra emissions are also captured. The demand for electricity decreased by about 60% (from 97 to 43 kWh/$t_{cement}$) compared to the reference case. This is possible due to the high-temperature heat in the flue gas leaving the CaL unit. The heat is also used for steam production and power generation in a Rankine cycle to cover the CPU and ASU demand as well as part of the cement production utilities.

#### 3.1.1.2 ECONOMIC ASSESSMENT

In terms of economics, the resulting cement production cost is estimated to 49 €/$t_{cement}$ in the reference plant (without CCS). The cement production cost in terms of OPEX and CAPEX for reference plant (with and without CCS), $CO_2$ capture cost and $CO_2$ avoided cost are presented in Table 3.2.

*Table 3.2 Cement production cost for the reference cement plant with and without CCS*

| **Cost** | **Reference scenario** | **CCS scenario** | |
|---|---|---|---|
| | | **Oxyfuel** | **CaL** |
| Variable OPEX (€/ $t_{cement}$) [a] | 19 | 32 | 34 |
| Fixed OPEX (€/t $t_{cement}$) | 14 | 20 | 24 |
| CAPEX (€/ $t_{cement}$) | 16 | 27 | 33 |
| Total production cost (€/$t_{cement}$) | 49 | 78 | 91 |
| $CO_2$ capture cost (€/$t_{CO2}$) [a] | | 51 | 50 |
| $CO_2$ avoided cost (€/$t_{CO2}$) [a] | | 53 | 75 |
| Delivery cost (€/$t_{cement}$) [b] | 6 | 6 | 6 |

[a] Includes $CO_2$ transport and storage cost
[b] Based on transport model, from cement plant to concrete production facilities

In the oxy-fuel case, there is a slight increase in coal consumption, compared to the reference scenario, and coal cost (€/$t_{cement}$) remains unchanged. An increase in the electricity demand, along with the cost related to $CO_2$ transport and storage cost (6 €/$t_{cement}$)[3], lead to a higher variable OPEX of about 70% compared to the reference case without CCS. Extra labor cost and maintenance costs are also required for increasing fixed OPEX by about 40%. CAPEX is about 70% higher than the capital cost in the reference plant, mainly due to investment in ASU, CPU, a rotatory kiln burner for oxyfuel combustion, recirculation system, heat exchangers, and ORC waste heat recovery system. For oxyfuel technology, a total cement production cost of about 78 €/$t_{cement}$ is estimated, which is about 60% higher than the production cost in the reference plant without CCS.

In the CaL tail-end configuration the demand for coal, compared to the reference scenario, increased about 130% (from 0.11 to 0.26 $t_{coal}$/$t_{cement}$) due to the fuel consumption in the CaL calciner. Also, the CaL process requires limestone supply. However, limestone is recirculated replacing part of the limestone in the raw materials. Therefore, the amount of the total limestone required for the cement process and CaL process remained unchanged. As is mentioned in section 4.1.1.1 the electricity demand decreased by about 60% compared to the reference case. An increase in the coal demand, along with the cost related to $CO_2$ transport and storage cost (9 €/$t_{cement}$)[1], lead to a higher variable OPEX of about 80% compared to the reference case without CCS. Extra labor cost and maintenance costs are also required for increasing fixed OPEX by about 70%. CAPEX is about 110% higher than the capital cost in the reference plant, mainly due to investment in carbonator and calciner reactors, CPU, ASU, and steam cycle waste heat recovery system. For CaL tail-end configuration, a total cement production cost of about 91 €/$t_{cement}$ is estimated, which is about 90% higher than the production cost in the reference plant without CCS.

Figure 3-1 presents a breakdown of the cement production cost into its main cost factors. It can be seen that in the reference scenario (without CCS) the cost of the raw materials represents 8%, fuel cost (e.g., coal) represents 16% and electricity cost represents 12% of the total production cost. Consequently, those costs are part of the variable OPEX (i.e., including miscellaneous costs) which represents 39% of the total production cost. Fixed OPEX and CAPEX represent 29% and 32% respectively. In CaL tail end technology electricity is produced covering the demand of the $CO_2$ capture process and also part of the electricity used in the cement production process. This is reflected in a lower electricity cost per ton of cement compared to the reference scenario. CaL technology presents a higher production cost than oxyfuel technology even though some electricity is generated in the process. This is explained due to CaL technology requires extra fuel (e.g., coal) consumption, in turn, more $CO_2$ emissions are generated and captured increasing the fuel cost and the $CO_2$ transport and storage cost (i.e., those costs are part of the variable OPEX). Also, CaL requires a higher investment cost and maintenance cost than oxyfuel technology. Finally, it can be seen that in oxyfuel technology the variable OPEX represents 41% and CAPEX represents 34% of the total

[3] $CO_2$ transport and storage cost depends on the amount of $CO_2$ that is captured. In CaL scenario, the amount of capture $CO_2$ is higher compared to the oxyfuel scenario. Therefore, the cost per tonne of cement is higher in CaL scenario.

production cost meanwhile in CaL tail end technology variable OPEX represents 38% and CAPEX represents 36% of the total production cost.

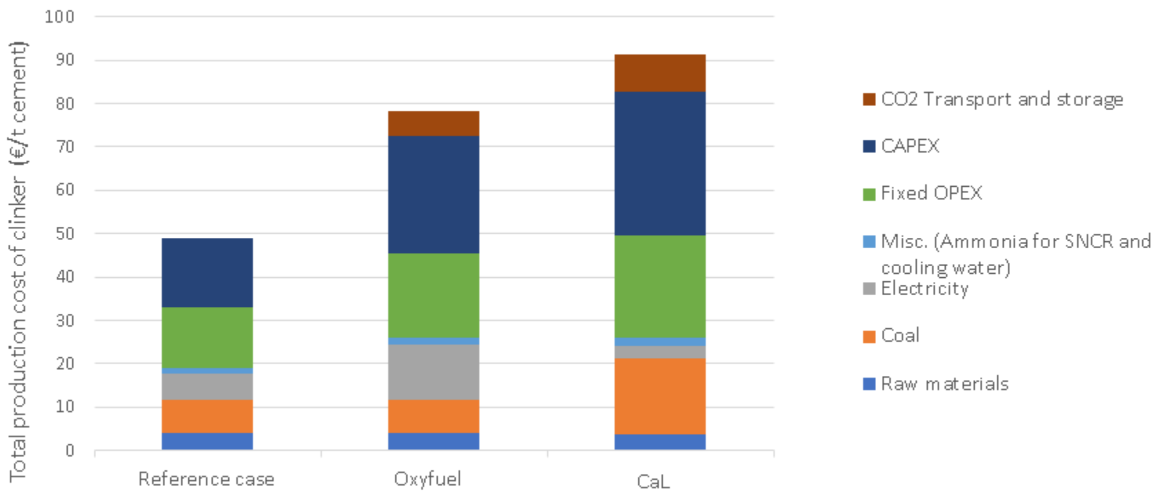



*Figure 3-1 Breakdown of the cement production cost in the reference cement plant with and without CCS.*

### 3.1.1.3 KEY PERFORMANCE INDICATORS

Table 3.3 presents the carbon footprint indicators and the economic indicators. CaL tail-end technology presents a slightly higher amount of $CO_2$ avoided as well as a higher captured $CO_2$ compared to oxyfuel technology (see section 4.1.1.1). Since $CO_2$ avoided cost and capture cost are inversely proportional to the amount of $CO_2$ respectively (i.e., either a higher $CO_2$ avoided or $CO_2$ captured a lower avoided cost or capture cost) it is expected that the avoided cost and capture cost for CaL are higher than its oxyfuel costs. However, this is not the case for the $CO_2$ avoided cost. Since there is almost the same amount of CO2 avoided in both technologies, a higher difference in the CaL production cost (i.e., this cost is also part of the $CO_2$ avoided cost) makes the $CO_2$ avoided cost higher than the value in the oxyfuel technology.

*Table 3.3 Key performance indicators for cement production*

| KPI's | Reference scenario | CCS scenario | |
|---|---|---|---|
| | | **Oxyfuel** | **CaL** |
| $CO_2$ capture ratio | | 90% | 94% |
| $CO_2$ capture cost (€/$t_{CO2}$) | | 51 | 50 |
| $CO_2$ avoided | | 90% | 91% |
| $CO_2$ avoided cost (€/$t_{CO2}$) | | 55 | 77 |
| Total production cost (€/$t_{cement}$) | 49 | 78 | 91 |
| Increase production cost | | 60% | 90% |

There is fuel and electricity consumption tradeoff between both capture technologies. For instance, electricity consumption is higher in oxyfuel meanwhile in the CaL process the electricity consumption is lower than the reference case without CCS. However, the CaL process rises coal consumption compared to the reference scenario and the oxyfuel scenario. As it has been presented in the assessment, consuming more coal leads to a higher production cost of cement compared to importing more electricity from the grid. Also, consuming more coal as fuel leads to generate more direct emissions that, in turn, are captured. It can be concluded that basically the same amount of $CO_2$ along the cement production are avoided in any of the capture technologies. However, oxyfuel technology presents a lower cement production cost, as well as lower CO2, avoided cost than CaL tail end technology. Also, avoiding 90% of the direct CO2 emissions has a considerable impact on the production cost at a higher cost between 60%-90%.

### 3.1.2 CONCRETE PRODUCTION

The $CO_2$ emissions estimation and cost estimation presented in this section are based on producing 1 $m^3$ concrete. It is assumed 340 kg of cement is required to produce 1 $m^3$ of concrete.

#### 3.1.2.1 CARBON FOOTPRINT ASSESSMENT

Table 3.4 presents the $CO_2$ emissions related to the production of 1 $m^3$ of concrete. It is assumed electricity required for the concrete production process is imported from the grid; thus, direct $CO_2$ emissions are not generated during concrete production. The carbon footprint of concrete production is formed by the $CO_2$ emissions generated during cement production and the emissions generated during the transport of cement and concrete.

*Table 3.4 $CO_2$ emissions related to concrete production*

| **$CO_2$ emissions** | **Reference scenario** | **CCS scenario** | |
|---|---|---|---|
| | | Oxyfuel | CaL |
| Cement production ($kg_{CO2}/m^3_{concrete}$) [a] | 213 | 22 | 20 |
| Cement delivery ($kg_{CO2}/m^3_{concrete}$) [ab] | 2 | 2 | 2 |
| Concrete delivery ($kg_{CO2}/m^3_{concrete}$) [c] | 15 | 15 | 15 |
| Total $CO_2$emissions ($kg_{CO2}/m^3_{concrete}$) | 230 | 39 | 37 |
| $CO_2$ avoided | | 83% | 84% |

[a] $CO_2$ emissions from production and transport of one tonne of cement are expressed per 340 kg of cement
[b] From cement plant to concrete production facilities
[c] From concrete plant to construction site

#### 3.1.2.2 ECONOMIC ASSESSMENT

In terms of economics, the resulting concrete production cost is estimated at 125 €/$m^3_{concrete}$ considering cement produced in the reference scenario (without CCS). The concrete production cost in terms of material cost, fixed cost, and plant cost considering production of cement with and without CCS are presented in Table 3.5. Delivery cost is included as part of the production cost. This cost is estimated based on the transport model (see section 2.2.2.3) and then added to the production cost.

*Table 3.5 Concrete production cost for different scenarios*

| | Reference scenario | CCS scenario | |
|---|---|---|---|
| | | Oxyfuel | CaL |
| Cement (€/$m^3_{concrete}$) [a] | 19 | 29 | 33 |
| Materials (€/$m^3_{concrete}$) | 44 | 44 | 44 |
| Delivery (€/$m^3_{concrete}$) [b] | 13 | 13 | 13 |
| Fixed cost and plant cost (€/$m^3_{concrete}$) | 49 | 49 | 49 |
| Total production cost (€/$m^3_{concrete}$) | 125 | 135 | 139 |

[a] Including delivery cost from the cement plant to concrete production facilities
[b] Estimated based on the transport model

Figure 3-2 shows a breakdown of the concrete production cost into its main cost factors. It can be seen that the cost of the raw materials (including cement) is the main contributor to concrete production cost by about 50% in the reference case and by about 55% in both CCS scenarios. Cement cost represents about 15% of the total production cost in the reference case while in the CCS scenarios represent about 20%.

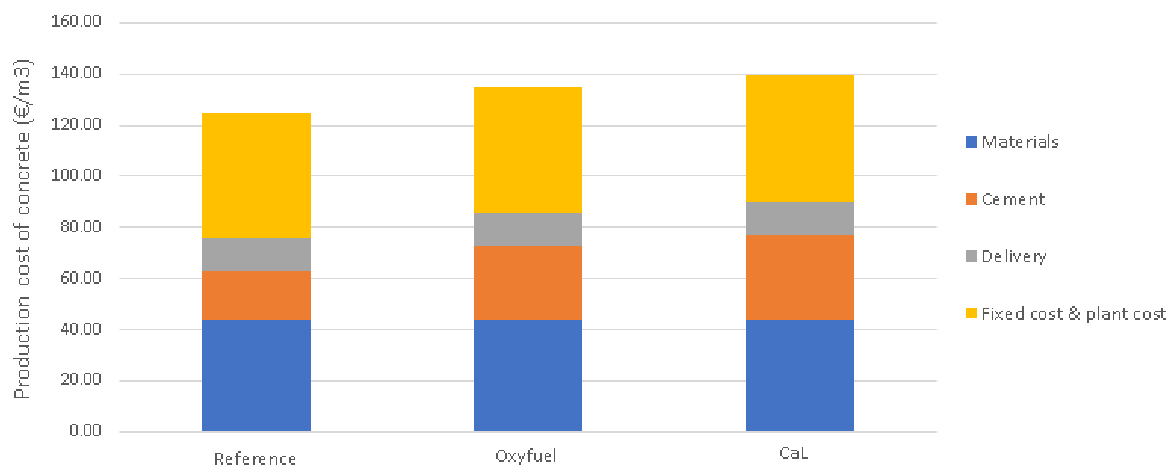



*Figure 3-2 Breakdown of the concrete production cost*

### 3.1.2.3 KEY PERFORMANCE INDICATORS

Table 3.6 presents the $CO_2$ emissions indicators and economic indicators. There is an increase in the production cost is about 10% in both CCS scenarios. Also, there is not a significant difference between the $CO_2$ avoided values for both capture technologies. The main factor contributing to an increase in the concrete production cost is the variation in cement production cost when CCS is implemented in its production. It can be concluded that an increment of 10% in the concrete cost represents to avoid about 80% of the $CO_2$ emissions from the cement production gate to the construction site gate. It should be noted that the avoided emissions are associated with the implementation of CCS in cement production.

*Table 3.6 _ Key performance indicators for concrete production*

| | Reference scenario | CCS scenario | |
|---|---|---|---|
| | | **Oxyfuel** | **CaL** |
| Total $CO_2$ emissions ($kg_{CO2}/m^3_{concrete}$) | 230 | 39 | 37 |
| $CO_2$ avoided | | 83% | 84% |
| Total production cost (€/$m^3_{concrete}$) | 125 | 135 | 139 |
| Increase production cost | | 8% | 12% |

## 3.1.3 STEEL PRODUCTION

The $CO_2$ emissions estimation and cost estimation presented in this section are based on an integrated steel mill plant with a capacity of 4Mt hot rolled coil (HRC) per year through a blast furnace route (BF-BOF). Coal and natural gas are used as fuel. Electricity is produced on-site in a natural gas power plant and steam is produced in a boiler. In the CCS scenario, an oxy-blast furnace (OBF) and using MDEA/Pz as capture technology are evaluated.

### 3.1.3.1 CARBON FOOTPRINT ASSESSMENT

In the reference scenario (without CCS) direct $CO_2$ emissions are generated from the blast furnace, the power plant, coke ovens, lime kilns, and sinter plant. In Table 3.7 an overview of $CO_2$ generated before and after capture, and $CO_2$ captured per source is presented.

*Table 3.7 Direct CO2 emissions of the reference steel plant with and without CCS*

| **Direct emissions ($t_{CO2}/t_{HRC}$)** | **Reference scenario** | **CCS scenario** |
|---|---|---|
| $CO_2$ generated (before capture) | 2 | |
| $CO_2$ captured | | 0.86 |
| $CO_2$ emitted (after capture) | | 1.1 |
| $CO_2$ avoided [a] | | 47% |

[a] Based on $CO_2$ emissions in the reference scenario (without capture)

Regarding $CO_2$ capture (OBF MDEA/Pz) in HRC production, the consumption of coking coal decreased about 20% (from 16 to 12 GJ/ $t_{HRC}$) compared to the reference case, due to the top gas recirculation in the OBF. The demand for natural gas increased by about 500% (from 0.8 to 5 GJ/ $t_{HRC}$), compared to the reference case, due to an increase in electricity production by the power plant, steam generation, OBF-PG heaters, and the ASU. Additional emissions generated by natural gas as a fuel are in turn captured.

Additional $CO_2$ emissions are generated during the finishing tasks to produce steel products (e.g., wire, rod, and structural steel). To represent these emissions 0.3 $t_{CO2}/t_{HRC}$ are added to the specific emissions of HRC before and after capture. In Table 3.8 the $CO_2$ emissions (with and without CCS) for different steel products are presented.

*Table 3.8 Direct CO2 emissions for different steel products.*

| **Steel product** | **Reference scenario ($t_{CO2}/t_{steel}$)** | **CCS scenario ($t_{CO2}/t_{steel}$)** |
|---|---|---|
| Wire/rod | 2.3 | 1.4 |
| Structural steel | 2.3 | 1.4 |
| Steel delivery ($kg_{CO2}/t_{steel}$) | 43 | 43 |

### 3.1.3.2 ECONOMIC ASSESSMENT

In terms of economics, the resulting HRC production cost is estimated at 393 €/t $_{HRC}$ in the reference plant (without CCS). The HRC production cost in terms of OPEX and CAPEX for reference plant (with and without CCS), $CO_2$ capture cost, and $CO_2$ avoided cost are presented in Table 3.9.

*Table 3.9 Steel production cost for different scenarios*

| | **Reference** | **OBF MDEA/Pz** |
|---|---|---|
| Variable OPEX (€/t $_{HRC}$)[a] | 181 | 207 |
| Fixed OPEX (€/t $_{HRC}$) | 102.1 | 108 |
| CAPEX (€/t $_{HRC}$) | 110 | 132 |
| Total production cost (€/t $_{HRC}$) | 393 | 447 |
| $CO_2$ capture cost (€/$t_{CO2}$) [a] | | 54 |
| $CO_2$ avoided cost (€/$t_{CO2}$) [a] | | 57 |
| Delivery cost [b] | 6 | 6 |

[a] Includes transport and storage cost

[b] Based on transport model, from cement plant to concrete production facilities

An increase in the natural gas consumption, along with the cost related to $CO_2$ transport and storage (9 €/$t_{HRC}$), lead to a higher variable OPEX of about 15% compared to the reference scenario without CCS. Extra labor cost and maintenance cost increase fixed OPEX by about 6%. CAPEX is about 20% higher than the capital cost in the reference scenario, mainly due to the investment in the steam generation unit and an ASU to produce oxygen. For the CCS scenario, a total HRC production cost if about 447 €/$t_{HRC}$ is estimated which is about 14% higher than the production cost in the reference scenario without CCS.

Figure 3-3 shows a breakdown of the HRC production cost into its main cost factors. In the reference scenario (without CCS) the cost of the raw materials represents 23%, fuel cost (e.g., natural gas and coal) represents 19%. Consequently, those costs are part of the variable OPEX (i.e., including consumables and others) which represents 46% of the total production cost. Fixed OPEX and CAPEX represent 24% and 39% respectively. In the CCS scenario, the variable OPEX share has slightly changed since there is lower coal consumption but a higher natural gas consumption to produce electricity as well as the $CO_2$ transport and storage cost is small. It can be seen that the main cost factor is the CAPEX in both scenarios, the main contributors (i.e., after the CAPEX and fixed OPEX) are the raw materials and the fuel (e.g., natural gas)

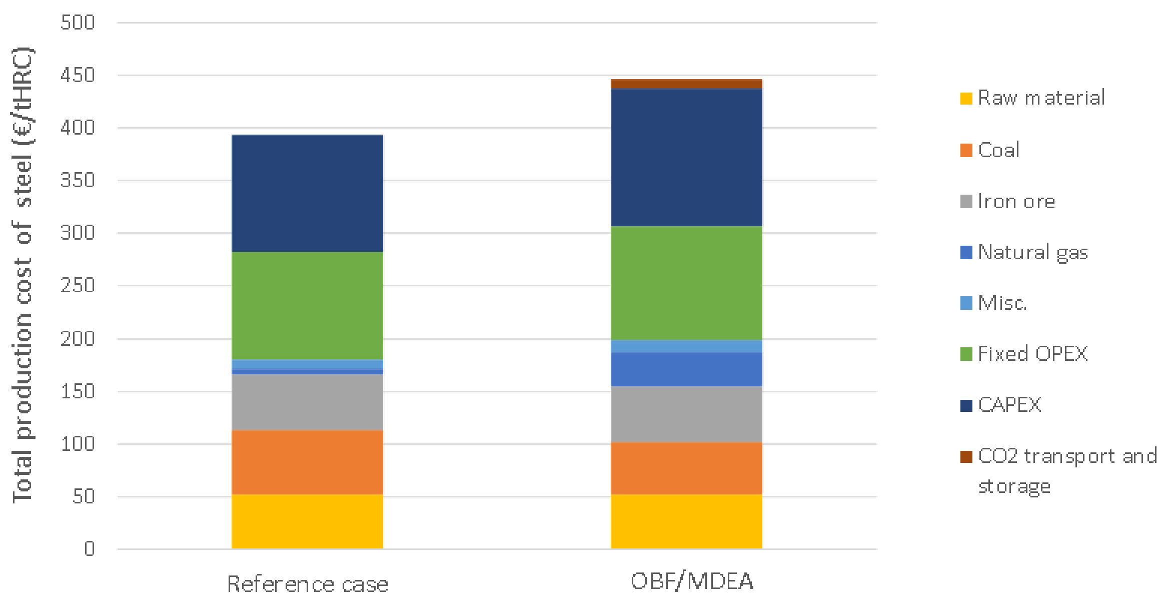



*Figure 3-3 Breakdown of the HRC production cost in the reference steel mill with and without CCS.*

Additional costs related to finishing tasks to produce steel products (e.g., wire, rod, and structural steel) are included. Based on (MEPS, 2018) wire and rod costs are equal to HRC production cost. Structural steel cost is equal to 1.23 of HRC production cost. In Table 3.10 steel production cost (with and without CCS) for different steel products is presented.

*Table 3.10 Production cost for different steel products.*

| Steel product | Reference scenario ($€/t_{steel}$) | CCS scenario ($€/t_{steel}$) |
|---|---|---|
| Wire/rod | 393 | 447 |
| Structural steel | 484 | 549 |
| Delivery cost [a] | 39 | 39 |

[a] Based on transport model, from steel mill plant to the construction site

#### 3.1.3.3 KEY PERFORMANCE INDICATORS

Table 3.11 presents the carbon footprint indicators and economic indicators. Avoiding 47% of the direct emissions in hot roll coil production has an impact on a higher production cost of about 14%. Additionally, capturing a tonne of $CO_2$ costs 62€.

*Table 3.11 Key performance indicators for HRC production*

| KPI's | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ capture cost (€/t$CO_2$) | | 62 |
| $CO_2$ avoided | | 47% |
| $CO_2$ avoided cost (€/t$CO_2$) | | 55 |
| Total production cost (€/tHRC) | 393 | 447 |
| Increase production cost | | 14% |

### 3.1.4 BRIDGE CONSTRUCTION

In this section, the $CO_2$ emissions and the building cost of the Lake Pontchartrain Causeway are presented. For its construction, about 225,000 $m^3$ of concrete (76487 tons of cement are used), and 24,000 tons of steel are used.

#### 3.1.4.1 CARBON FOOTPRINT ASSESSMENT

The direct CO2 emissions associated with the Lake Pontchartrain Causeway are given by the sum of direct $CO_2$ emissions in cement and steel production (i.e., the concrete production process does not generate direct $CO_2$ emissions), and emissions during transport. Transport emissions remain fixed over both scenarios (reference and CCS) meaning that the variation in $CO_2$ emissions is directly related to the primary production process.

Table 3.12 presents the total $CO_2$ emissions along the value chain for all scenarios. The carbon footprint assessment indicates that about 60% of the total $CO_2$ emissions along the value chain are avoided by CCS implementation in primary production.

*Table 3.12 Total CO2 emissions for all scenarios*

| **$CO_2$ emissions (kt)**[4] | **Reference** | **Oxyfuel** | **CaL** |
|---|---|---|---|
| Cement production | 48 | 5 | 4.5 |
| Cement delivery | 0.5 | 0.5 | 0.5 |
| Concrete delivery | 3 | 3 | 3 |
| Steel production | 58 | 34 | 34 |
| Steel delivery | 1 | 1 | 1 |
| Total $CO_2$ emissions | 111 | 44 | 43 |
| $CO_2$ avoided | | 60% | 61% |

Figure 3-4 shows a breakdown of the $CO_2$ emissions along the value chain with and without CCS implementation in cement and steel production. It can be seen that in the reference scenario cement and steel productions are the main contributors of $CO_2$ emissions along the value chain. For instance, cement production represents 43% (48kt $CO_2$) meanwhile steel represents 52% (58kt $CO_2$) of the total $CO_2$ emissions. Emissions during transport of cement, steel and concrete represent the remaining 5% of the total emissions. Moreover, the main contributor of emissions reduction is the avoided emissions in cement production where about 90% of the direct emissions are avoided meanwhile about 50% of the direct emissions are avoided in steel production. It can be concluded that implementing CCS in cement and steel production helps to avoid 60% of the total $CO_2$ emissions along the value chain.

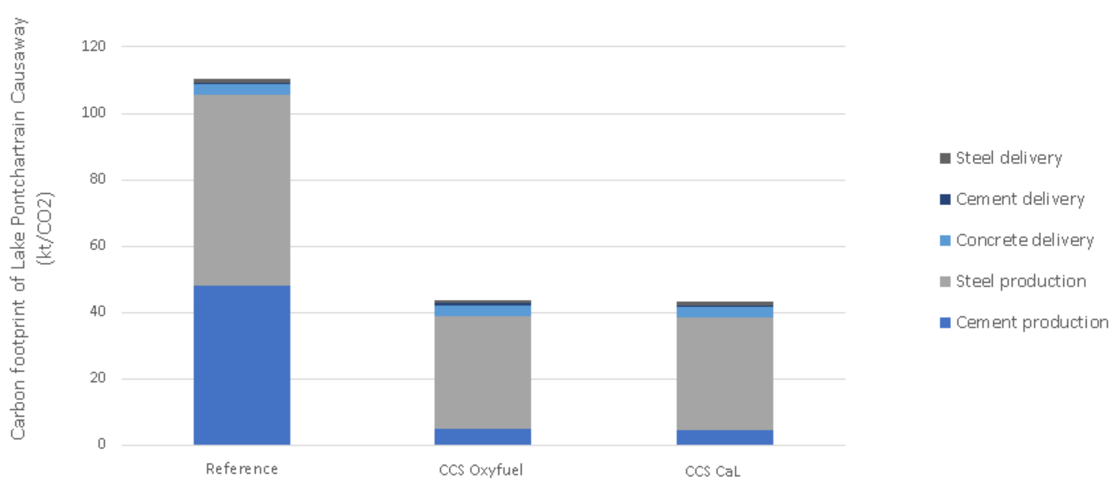



*Figure 3-4 Breakdown of direct CO2 emissions along the value chain.*

[4] Estimated based on specific emissions and the total amount of material used in the construction. For instance, $(0.63 t_{CO2}/t_{cement})*(76487\ t_{cement}) = 48 ktCO_2$

### 3.1.4.2 ECONOMIC ASSESSMENT

In terms of economics, the bridge total construction cost is categorized into four elements: superstructure, substructure, services and ancillaries, and site preparation. In turn, the superstructure is divided into other elements, including the cost of the material. In Table 3.13 the construction material cost is presented for all scenarios.

*Table 3.13 Total material cost with and without CCS for Lake Pontchartrain Causeway*

| **Material cost (M€)[5]** | **Reference** | **CCS** | |
|---|---|---|---|
| Steel [b] | 11 | 12 | |
| | | **Oxyfuel** | **CaL** |
| Concrete [a] | 28 | 30 | 31 |
| **Total material cost** | **39** | **42** | **43** |

[a] Including cement cost, delivery cost from the cement plant to concrete production facilities, and delivery cost from the concrete plant to construction site.
[b] Including delivery cost from steel plant to the construction site.

In Table 3.14 the superstructure cost is presented. It can be seen the material cost related to the fabrication of preassembled parts of steel and concrete are also included in this category.

*Table 3.14 Construction cost of the superstructure with and without CCS*

| **Construction cost (M€)** | **Reference** | **Oxyfuel** | **CaL** |
|---|---|---|---|
| Cost of material | 39 | 42 | 43 |
| Manufacturing beam | 81 | 81 | 81 |
| Concrete placing | 3 | 3 | 3 |
| Deck finishing | 0.3 | 0.3 | 0.3 |
| Rebar fabrication/placing | 14 | 14 | 14 |
| Supporting post | 10 | 10 | 10 |
| Form work | 9 | 9 | 9 |
| Slab waterproofing | 6 | 6 | 6 |
| Miscellaneous | 1 | 1 | 1 |
| Total | 162 | 165 | 166 |

In Table 3.15 the cost of each category; superstructure, substructure, services and ancillaries and site preparation are presented. It can be seen the resulting construction cost of Lake Pontchartrain Causeway is estimated to 383M€ in the reference case (without CCS).

[5] Estimated based on material production cost and and the total amount of material used in the construction. For instance, (126€/$m^3_{concrete}$)*( 225,000 $m^3$ of concrete)= 28M€

*Table 3.15 Total construction cost of the bridge with and without CCS*

| Construction cost (M€) | Reference | Oxyfuel | CaL |
|---|---|---|---|
| Superstructure | 162 | 165 | 166 |
| Services & ancillaries | 44 | 44 | 44 |
| Site preparation | 20 | 20 | 20 |
| Substructure work | 158 | 158 | 158 |
| Total | 383 | 386 | 387 |

Figure 3-5 presents a breakdown of the construction cost and its share for a reference case and CCS scenarios. It can be seen that in the reference scenario (without CCS) the material cost represents 24% of the superstructure cost. However, the superstructure cost represents 42% of the total construction cost. Therefore, the material cost represents 10% of the total construction cost. In CCS scenarios the material cost represents about 11% of the total construction cost. It can be concluded that implementing CCS in cement and steel production has a negligible impact on the material cost and, in turn, in the total construction of the Lake Pontchartrain Causeway.

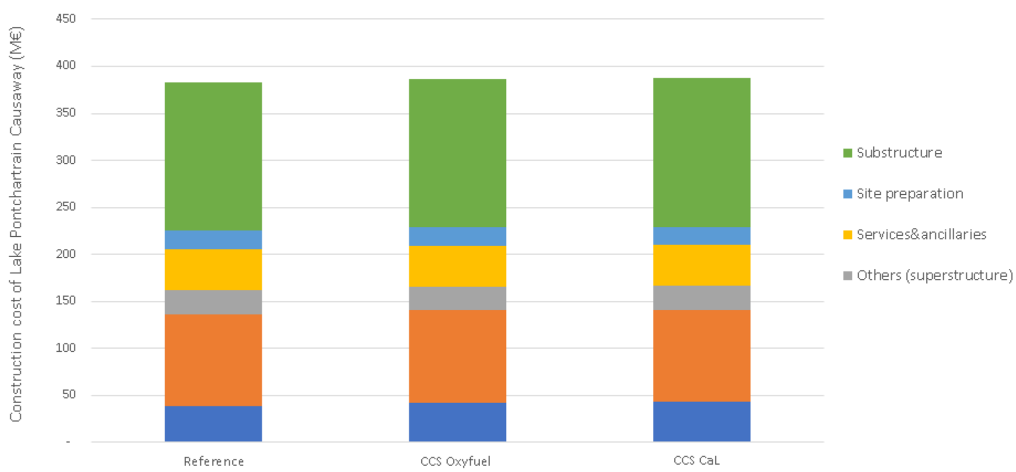



*Figure 3-5 Breakdown of the Lake Pontchartrain Causeway construction cost for all scenarios.*

### 3.1.4.3 KEY PERFORMANCE INDICATORS

Table 3.16 presents the carbon footprint indicators and economic indicators. Avoiding about 40% of the direct emissions in the production of the construction materials has an impact on a higher material cost of about 11%. In turn, the total construction cost of the bridge is higher by about 1% when CCS is implemented in primary production. It can be concluded that avoiding 60% of the direct $CO_2$ emissions along the value chain by implementing CCS in cement and steel production has a negligible impact on the construction cost of the bridge.

*Table 3.16 Key performance indicators of bridge*

| | Reference | CCS | |
|---|---|---|---|
| Total cost of steel (M€) | 11 | 12 | |
| | | Oxyfuel | CaL |
| Total cost of concrete (M€) | 28 | 30 | 31 |
| Total material cost (M€) | 39 | 42 | 43 |
| Increase | | 11% | 11% |
| Construction cost (M€) | 383 | 386 | 387 |
| Increase | | 0.9% | 1.2% |
| Total $CO_2$ emissions (kt) | 111 | 44 | 43 |
| $CO_2$ avoided | | 60% | 61% |

## 3.2 CASE STUDY II: CORN

In this case study ammonia is defined as a primary product and urea as an intermediate product. However, since urea production is integrated into ammonia facilities the results are expressed for an integrated ammonia/urea plant (i.e., expressed per tonne of urea). Those results include the emissions and production costs related to ammonia production.

### 3.2.1 AMMONIA/UREA PRODUCTION

The $CO_2$ emissions estimation and cost estimation presented in this section are based on an integrated ammonia/urea plant with a capacity of 449.5 kt ammonia ($NH_3$) per year through the Haber-Bosch process and 752.6 kt urea per year. Natural gas is used as feedstock and fuel. Electricity is imported from the grid. In the CCS scenario, the urea production is maximized to 792.5 kt/y (i.e., all ammonia is converted into urea, and part of the captured $CO_2$ is used as feedstock). Also, an absorption process using MEA solvent as capture technology is evaluated. It should be noted that although ammonia and urea are different products (i.e., primary and intermediate products respectively) the urea production is integrated into ammonia production facilities. Therefore, the direct $CO_2$ emissions and production cost are expressed per tonne of urea (i.e., those includes the ammonia cost and its emissions). Also, in the reference scenario, only 95% of the ammonia is converted into urea. In the CCS scenario, 100% of the ammonia is converted into ammonia and about 13% of the captured $CO_2$ is used as a feedstock to increase the urea production.

#### 3.2.1.1 CARBON FOOTPRINT ASSESSMENT

In Table 3.17 the direct emissions before and after capture, the $CO_2$ captured, the capture ratio, and the $CO_2$ avoided in each scenario are presented. In the reference scenario (without CCS) direct $CO_2$ emissions are generated from the primary reformer as consequence of fossil fuel combustion. It is worth mentioning the $CO_2$ that is removed form the syngas does not count as part of the direct emissions since it is used as a feedstock in downstream production of urea.

*Table 3.17 Direct CO2 emissions of the reference integrate ammonia/urea plant with and without CCS*

| **$CO_2$ emissions** | **Reference scenario** | **CCS scenario** |
|---|---|---|
| $CO_2$ generated (before capture) ($t_{CO2}/t_{urea}$) | 0.33 | |
| $CO_2$ captured ($t_{CO2}/t_{urea}$) | | 0.31 |
| $CO_2$ to urea plant ($t_{CO2}/t_{urea}$) | | 0.04 |
| $CO_2$ product ($t_{CO2}/t_{urea}$) [a] | | 0.24 |
| $CO_2$ emitted (after capture) ($t_{CO2}/t_{urea}$) | | 0.03 |
| $CO_2$ avoided [b] | | 90% |
| Urea delivery [d] ($kg_{CO2}/t_{urea}$) | | 6.6 |

[a] $CO_2$ to transport and storage

[b] Based on $CO_2$ emissions in the reference scenario (without capture)

Regarding $CO_2$ capture in ammonia/urea production, the consumption of electricity increased by about 90% compared to the reference case. This can be explained since the capture unit consumes electricity (i.e., instead of fossil fuel), as well as some compressor, are modified into electrical driven compressors.  The demand for natural gas as feedstock r is unchanged as well as the natural gas used as fuel in the primary reformer burners. It should be noted that since electricity is imported from the grid no extra $CO_2$ emissions are generated by the capture unit.

### 3.2.1.2 ECONOMIC ASSESSMENT

In terms of economics, the resulting urea production cost is estimated at 273 €/$t_{urea}$ in the reference scenario (without CCS). The urea production cost in terms of OPEX and CAPEX for the reference plant (with and without CCS), $CO_2$ capture cost and $CO_2$ avoided cost are presented in Table 3.18.

*Table 3.18 Urea production cost for the reference cement plant with and without CCS*

| **Cost** | **Reference scenario** | **CCS scenario** |
|---|---|---|
| Variable OPEX (€/ $t_{urea}$) [a] | 127 | 134 |
| Fixed OPEX (€/t $t_{curea}$) | 32 | 33 |
| CAPEX (€/ $t_{urea}$) | 111 | 118 |
| Total production cost (€/$t_{urea}$) | 269 | 285 |
| Delivery cost (€/$t_{urea}$) [b] | 6 | 6 |
| Urea cost (€/$t_{urea}$)[c] | 275 | 291 |
| $CO_2$ capture cost | | 58 |
| $CO_2$ avoided cost (€/$t_{CO2}$) [a] | | 60 |

[a] Includes $CO_2$ transport and storage cost

[b] Based on transport model, from ammonia/urea plant to farming site
[c] Production cost and delivery cost

An increase in electricity consumption, along with the cost related to $CO_2$ transport and storage (2.4 €/$t_{urea}$) lead to a higher variable OPEX of about 6% compared to the reference scenario without CCS. Extra labor cost and maintenance cost increase fixed OPEX by about 6%. CAPEX is about 7% higher than the capital cost in the reference scenario, mainly due to the investment in the capture unit (i.e., including $CO_2$ absorption section, heat exchanger network, and the $CO_2$ stripper section). For the CCS scenario, the total production cost of 285 €/$t_{urea}$ is estimated which is about 6% higher than the production cost in the reference scenario without CCS.

Figure 3-6 presents a breakdown of the urea production cost into its main cost factors. In the reference scenario (without CCS) natural gas as feedstock represents 32% of the total production cost and natural gas as fuel represents 12%. Consequently, those costs are part of the variable OPEX (i.e., chemicals and catalyst) which represents 47% of the total production cost. Fixed OPEX and CAPEX represent 12% and 41% respectively. In the CCS scenario, the variable OPEX share increases since there is more electricity consumption compared to the reference case as well as considering the $CO_2$ transport and storage cost. Also, has slightly changed since there is lower coal consumption but a higher natural gas consumption to produce electricity as well as the $CO_2$ transport and storage cost is small. the main cost factor is the CAPEX in both scenarios, the second main contributor is the feedstock of natural gas.

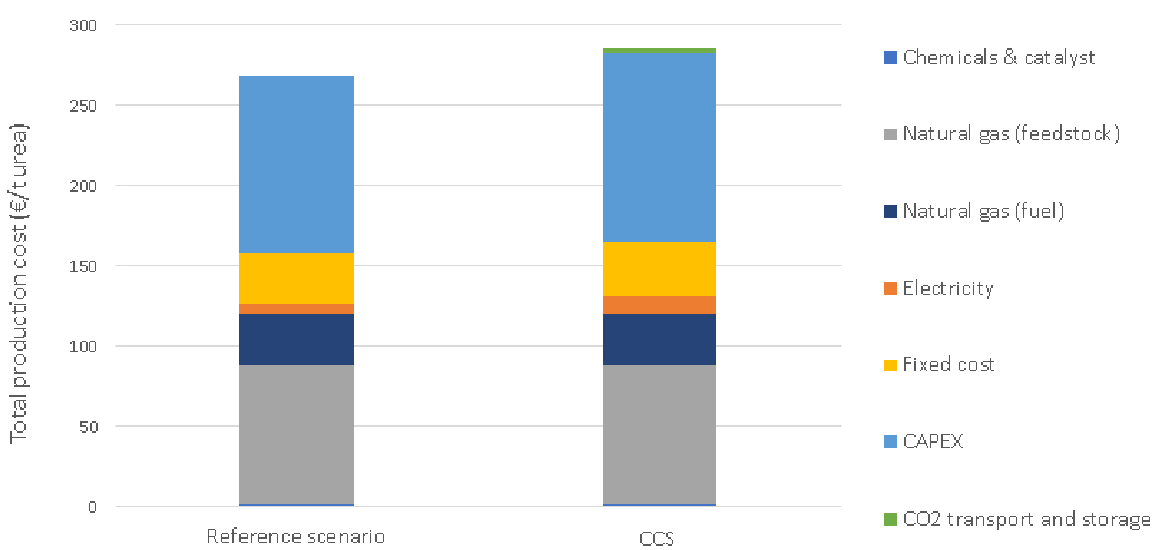



*Figure 3-6 Breakdown of the urea production cost in the reference integrated plant with and without CCS.*

### 3.2.1.3 KEY PERFORMANCE INDICATORS

In Table 3.19 the $CO_2$ emissions indicators and the economic indicators are presented. Avoiding the 85% of the direct emissions in urea production has an impact on a higher urea production cost of about 6%.

*Table 3.19 Key performance indicators for ammonia/urea production*

| KPI's | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ avoided | | 90% |
| $CO_2$ capture cost (€/$t_{CO2}$) | | 58 |
| $CO_2$ avoided cost (€/$t_{CO2}$) | | 60 |
| Total production cost (€/$t_{urea}$) | 269 | 285 |
| Increase production cost | | 6% |

## 3.2.2 CORN CROP

In this section, the $CO_2$ emissions and the farming cost of corn are presented. The results are presented per planted acre in which 0.5 tonnes of urea is used as fertilizer.

### 3.2.2.1 CARBON FOOTPRINT ASSESSMENT

The corn crop carbon footprint assessment is given by the sum of the direct $CO_2$ emissions in the ammonia/urea production and emissions during transport.

Table_ presents the total $CO_2$ emissions along the value chain for reference and CCS scenario. The carbon footprint assessment indicates that about 89% of the total $CO_2$ emissions along the value chain (i.e., from ammonia/urea producer gate to farming gate).

Table_. Carbon footprint assessment of corn per planted acre for different scenarios

| $CO_2$ emissions (kg)[6] | Reference | CCS |
|---|---|---|
| Fertilizer (urea) | 163 | 49 |
| Urea delivery | 3.3 | 3.3 |
| Total $CO_2$ emissions | 166 | 28 |
| $CO_2$ avoided | | 89% |

Figure 3-7 presents a breakdown of the $CO_2$ emissions along the value chain (i.e., from ammonia/urea producer gate to farming gate) with and without CCS implementation in the

[6] Estimated based on specific emissions and the total amount of fertilizer used in one acre. For instance, ($325kg_{CO2}/t_{urea}$)*( 0.5 $t_{fertilizer}$ )= 163 $kgCO_2$

ammonia/urea. In the reference scenario, ammonia/urea production is the main contributor to $CO_2$ emissions. For instance, ammonia/urea production represents 98% (163 kg $CO_2$). Emissions during transport represent the remaining 2% of the total emissions. Therefore, the main contributor to emissions reduction is the avoided emissions in the ammonia/urea production where about 855 of the direct emissions are avoided. It can be concluded that implementing CCS in ammonia production helps to avoid 83% of the total $CO_2$ emissions along the value chain.

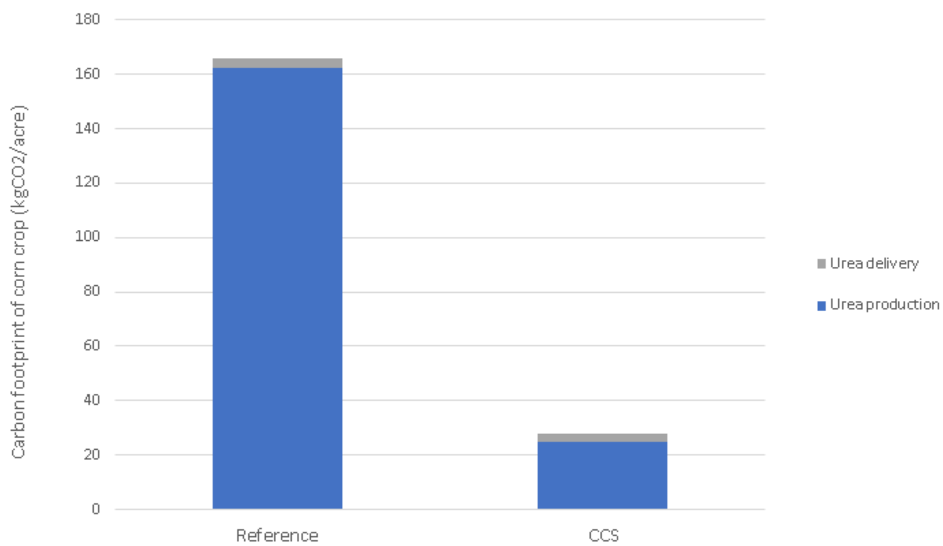



*Figure 3-7 Breakdown of the direct CO2 emissions for corn crop*

#### 3.2.2.2 ECONOMIC ASSESSMENT

In terms of economics, the farming cost is represented by the operating cost (i.e., excluding labor cost). In Table 3.20the operating costs per planted acre are presented for all scenarios.

*Table 3.20 Operating cost per planted acre*

| **Operating cost [a] €$_{2018}$** | **Reference** | **CCS** |
|---|---|---|
| Fertilizer[7] | 137 | 146 |
| Seed | 66 | 66 |
| Chemicals | 19 | 19 |
| Custom operations | 12 | 12 |
| Fuel, electricity | 21 | 21 |
| Irrigation water | 17 | 17 |
| Total | 273 | 281 |

[a] Excluding labor cost

[7] Estimated based on fertilizer (urea) production cost and the amount of fertilizer used per acre. For instance, (275€/$t_{urea}$)*( 0.5 $t_{fertilizer}$ )= 137€

Figure 3-8 presents a breakdown of the operating cost its main cost factors. In the reference scenario the fertilizer cost represents 50% of the total operating cost followed by the seed cost that represents a 24% of the total operating cost. It can be concluded that, although the fertilizer cost represents 50% of the total cost, a cost increment in the fertilizer is negligible in the CCS scenario.

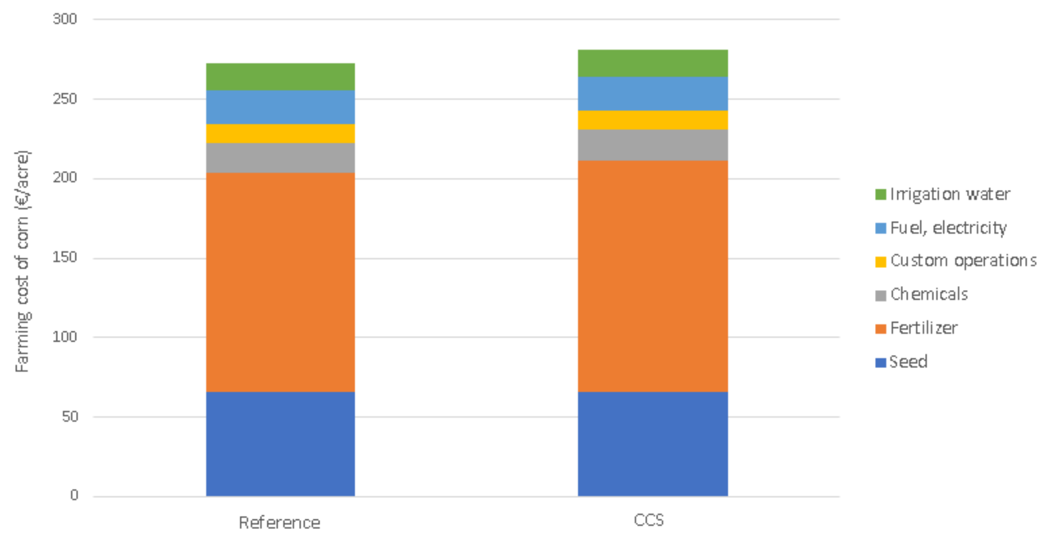



*Figure 3-8 Breakdown of the operating cost per planted acre for all scenarios*

### 3.2.2.3 KEY PERFORMANCE INDICATORS

In Table 3.21 the $CO_2$ emissions indicators and the economic indicators along the value chain are presented. It can be concluded that avoiding 83% of the direct $CO_2$ emissions along the value chain by implementing CCS in ammonia production has a little impact of about 6% on the corn production per acre.

*Table 3.21 Key performance indicators for corn production*

| **KPI's** | **Reference** | **CCS** |
|---|---|---|
| Production cost (€/t urea) | 269 | 285 |
| Increase | | 6% |
| Corn production cost (€/acre) | 273 | 281 |
| Increase | | 3% |
| $CO_2$ avoided [a] | | 83% |

[a] Including $CO_2$ emissions during transport

## 3.3 CASE STUDY III:

In this case study, the production cost is estimated differently. In an oil refinery, the cost of crude and the product prices are required to estimate the optimum product yield (IEAGHG, 2017c). In this case, the production cost is not expressed per tonne of product (e.g., €/$t_{propylene}$). However, to estimate the refinery processing cost (i.e., processing cost per oil barrel) the cost of the feedstock (e.g., crude oil and imported vacuum gasoil) is not required (IEAGHG, 2017c). Since the aim of the case study is to allocate the CCS cost and evaluate the reduction of emissions in the refinery plant, first the oil refinery processing cost and its emissions are estimated. Then, it is evaluated how to allocate the CCS cost in propylene production.

### 3.3.1 OIL REFINERY

The $CO_2$ emissions estimation and cost estimation presented in this section are based on an oil refinery with a capacity of 350,000 barrels per day producing 197 kt of propylene per year. Electricity and steam, are generated on-site by a natural gas power plant. A post-combustion capture based on MEA solvent is evaluated as a capture technology. It should be noted the refinery processing cost includes the annualized refinery CAPEX and the annual refinery OPEX (e.g., variable and fixed costs). Crude cost is excluded from the processing cost due to the complexity to determine the product yield. The direct $CO_2$ emissions are also reported as annual emissions.

#### 3.3.1.1 CARBON FOOTPRINT ASSESSMENT

In Table 3.22 the direct emissions before and after capture, the $CO_2$ captured, the capture ratio, and the $CO_2$ avoided in each scenario are presented. In the reference scenario (without CCS) direct $CO_2$ emissions are generated in every unit along the refining process (see section). In the CCS case, the capture is done in the crude distillation unit, vacuum distillation unit, steam methane reformer, fluid catalytic cracker, and the combined heat and power (CHP) plant (i.e., the emissions from the extra CHP plant are not captured).

*Table 3.22 Direct CO2 emissions of the reference oil refinery plant with and without CCS*

| Direct emissions ($kt_{CO2}$/y) | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ generated (before capture) | 3351 | 3989 [a] |
| $CO_2$ captured [b] | | 2769 |
| $CO_2$ emitted (after capture) | | 1220 |
| $CO_2$ avoided [c] | | 64% |

[a] Includes $CO_2$ emissions from the extra CHP plant
[b] $CO_2$ emissions from the extra CHP plant are not captured
[c] Based on $CO_2$ emissions in the reference scenario (without capture)

Regarding $CO_2$ capture in the oil refinery, the consumption of natural gas increased by about 180% compared to the reference case. This can be explained since natural gas is used as fuel in the extra

CHP is required in the CCS scenario to supply the steam and power demand by the capture and compression units.

#### 3.3.1.2 ECONOMIC ASSESSMENT

In terms of economics, the resulting processing cost is estimated at 1,500 M€ in the reference scenario (without CCS). The additional cost of implementing CCS (i.e., annualized CAPEX of CCS and annual OPEX of CCS) is estimated at 302 M€/y. The processing cost in terms of OPEX and CAPEX for the reference oil refinery (with and without CCS), $CO_2$ capture cost and $CO_2$ avoided cost are presented in Table 3.23

*Table 3.23 Processing cost for the reference oil refinery plant with and without CCS*

| Cost | Reference scenario | CCS scenario |
|---|---|---|
| Variable OPEX (M€/y) [a] | 297 | 419 |
| Fixed OPEX (M€/y) | 372 | 417 |
| CAPEX (M€/y) | 831 | 966 |
| Total processing cost (M€/y) | 1501 | 1803[b] |
| $CO_2$ capture cost (€/$t_{CO2}$) | | 109 |
| $CO_2$ avoided cost (€/$t_{CO2}$) [a] | | 142 |

[a] Includes $CO_2$ transport and storage cost
[b] Total processing cost in the reference scenario and the additional cost of implementing CCS (302 M€/y)

An increase in natural gas consumption, along with the cost related to $CO_2$ transport and storage, leads to a higher variable OPEX compared to the reference scenario without CCS. The increment in the CAPEX is due to the investment in the capture units (i.e., including $CO_2$ absorption section, heat exchanger network, and the $CO_2$ stripper section).

Figure 3-9presents a breakdown of the processing cost into its main cost factors. In the reference scenario (without CCS) natural gas represents 4% of the total processing cost. Variable OPEX represents 20%, fixed OPEX represents 23%, and CAPEX 54% respectively. In the CCS scenario share increases since there is more natural gas consumption compared to the reference scenario as well as considering the $CO_2$ transport and storage cost. The main cost factor that contributes to the processing cost in each scenario is the CAPEX, the second main contributor is the fixed OPEX.

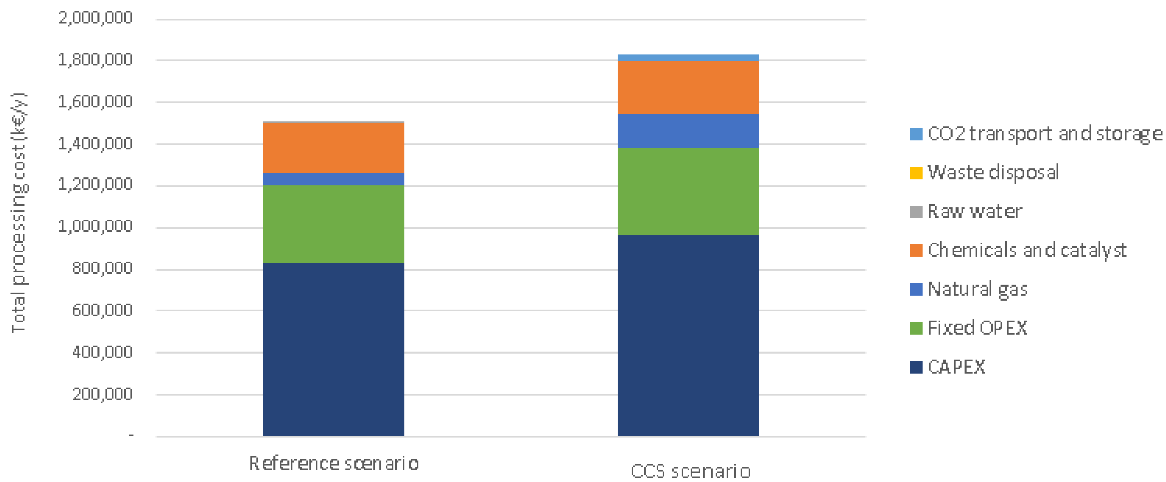



*Figure 3-9 Breakdown of the processing cost in the reference oil refinery plant with and without CCS.*

### 3.3.1.3 KEY PERFORMANCE INDICATORS

In Table 3.24 the carbon footprint indicators and the economic indicators are presented. Avoiding 64% of the annual direct emissions during the refining process has an impact on the annual processing cost increasing its cost by about 20%

*Table 3.24 Key performance indicators in the reference oil refinery plant*

| KPI's | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ avoided | | 64% |
| $CO_2$ capture cost (€/$t_{CO2}$) | | 109 |
| $CO_2$ avoided cost (€/$t_{CO2}$) | | 142 |
| Total processing cost (M€/y)[a] | 1501 | 1803 |
| Increase processing cost | | 20% |

[a] 302 M€ is the CCS cost

## 3.3.2 PROPYLENE PRODUCTION

### 3.3.2.1 CARBON FOOTPRINT ASSESSMENT

In Table 3.25 the Specific $CO_2$ emissions related to propylene production before and after capture are presented. These emissions are estimated based on the $CO_2$ emitted annually in the refinery and the annual propylene production. $CO_2$ avoided cost and $CO_2$ capture cost are not estimated since a propylene production cost is not estimated.

*Table 3.25 Specific CO2 emissions of propylene production in the reference oil refinery plant with and without CCS*

| Direct emissions ($t_{CO2}/t_{propylene}$) | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ generated (before capture) | 0.20 | 0.07 |
| $CO_2$ emitted (after capture) | | 0.07 |
| $CO_2$ avoided | | 64% |

### 3.3.2.2 CCS COST ALLOCATION

The difference in the processing cost between the CCS scenario and the reference scenario is 302 M€. This the 302 M€ additional costs of implementing CCS (i.e., annualized CAPEX of CCS and annual OPEX of CCS) per year is allocated to propylene production using two cost allocation approaches; using mass-based allocation and energy-based allocation.

Table 3.26 presents the share of mass content (SMC), the share of energy content (SEC) values, and the share of the additional cost of implementing CCS respectively. In product streams (e.g., 1a and 2a) about 1% of the CCS cost is allocated to propylene production. However, there is a significant difference (about double of the value) when the cost is allocated through the product streams (e.g., 1a and 2a) compared to when the cost is allocated through the process streams (e.g., 1b and 2b). Additionally, there is a negligible difference in the SMC and SEC values between mass-based allocation and energy-based allocation

*Table 3.26 Mass and energy-based allocation and its respective cost of implementing CCS*

| Approach 1: Mass-based allocation | | |
|---|---|---|
| | SMC | M€/y [a] |
| 1a: product streams | 1.1% | 3.5 |
| 1b: process streams | 2% | 6.1 |
| **Approach 2: Energy-based allocation** | | |
| | SEC | M€/y [a] |
| 2a: product streams | 1.3% | 3.8 |
| 2b: process streams | 2.1% | 6.3 |

[a] 302 M€/y multiplied by its respective SMC or SEC. The values are rounded.

Since there is not an estimation of production cost per tonne of propylene it is difficult to determine how much the production cost would increase after allocation of CCS cost. However, a broad estimation can be done based on mass-balance allocation using product streams (1a); refinery processing cost with and without CCS multiplied by its SMC (1.1%).

Table 3.27 presents a broad estimation of processing costs allocated to propylene production. The annual processing cost of propylene with CCS 20% higher compared to the reference scenario.

*Table 3.27 Propylene processing cost with and without CCS.*

| Processing cost (€/t $_{propylene}$) | Reference scenario | CCS scenario |
|---|---|---|
| Total processing cost (M€/y) | 1501 | 1803 |
| Propylene Processing cost (M€/y) | 17 | 21 |
| Increment | | 20% |

## 3.3.3 PROPYLENE OXIDE, POLYOL, AND FOAM

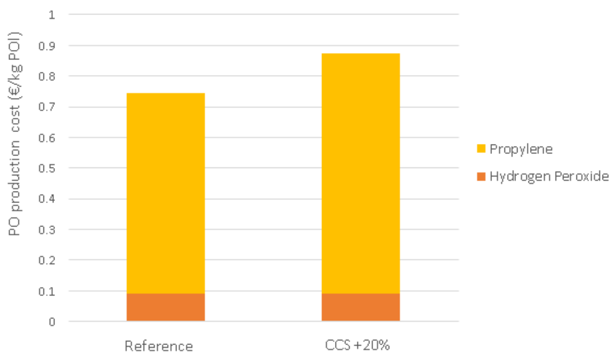
### 3.3.3.1 ECONOMIC ASSESSMENT

Since the propylene production cost (€/t$_{propylene}$) is not estimated in this study, the commercial price of propylene in 2018 is considered the production cost to estimate polyol and foam costs. It is assumed the increment in the propylene processing cost explained above is the increment in the production cost of propylene.

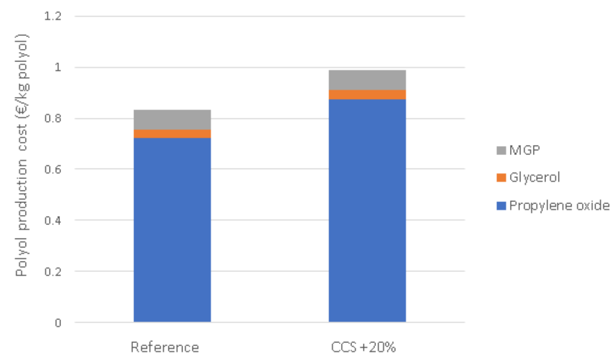
*Table 3.28 Production cost of propylene, polyol, and foam for different scenarios*

| | **Reference scenario** | **CCS scenario** |
|---|---|---|
| Propylene (€/kg $_{propylene}$) | 0.85 | 1.02 |
| Increment | | 20% |
| Propylene oxide (€/kg $_{PO}$) | 0.74 | 0.88 |
| Increment | | 18% |
| Polyol (€/kg $_{polyol}$) | 0.83 | 0.96 |
| Increment | | 15% |
| Foam (€/kg $_{foam}$) | 1.4 | 1.6 |
| Increment | | 9% |

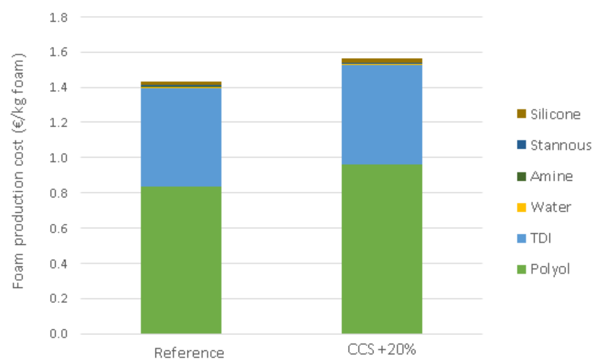
Figure 3-10 (a) presents a breakdown of polyol material cost into its main cost factors. In the reference scenario (without CCS) propylene cost represents 93% of the total production cost. Figure 3-10(b) presents a breakdown of foam material cost into its main cost factors. In the reference scenario, the polyol cost represents 58% of the total production cost.




(a)




(b)




(c)

*Figure 3-10 Breakdown of propylene oxide, polyol, and foam production cost whit and without CCS in propylene production.*

## 3.3.4 MATTRESS

### 3.3.4.1 CARBON FOOTPRINT ASSESSMENT

Table 3.29 presents the direct $CO_2$ emissions related to the materials required to produce 1 queen mattress. It is assumed that not direct emissions are generated during polyol and foam production; thus, the carbon footprint of mattress production is formed by the $CO_2$ generated during the propylene production.

*Table 3.29 Specific CO2 emissions of the materials used in mattress production*

| Direct emissions [8] | Reference scenario | CCS scenario |
|---|---|---|
| $CO_2$ generated ($kg_{CO2}$/mattress) | 2 | 0.7 |
| $CO_2$ avoided | | 65% |

[8] Estimated based on propylene specific emissions and the amount of propylene used per mattress.

### 3.3.4.2 ECONOMIC ASSESSMENT

In terms of economics, the mattress cost is represented by the production cost (i.e., excluding labor cost). In Table 3.30 the production cost per queen mattress is presented for all scenarios.

*Table 3.30 Production cost for queen mattress*

| **Production cost €$_{2018}$** | **Reference** | **CCS** |
|---|---|---|
| Foam cost[9] | 14 | 16 |
| Outer fabric | 2.4 | 2.4 |
| Quilting | 0.3 | 0.3 |
| Quilting foam cost | 1.2 | 1.2 |
| Total | 18 | 20 |

Table 3.30 presents a breakdown of the production cost its main cost factors. In the reference scenario the foam cost represents 78% of the total operating cost followed by outer fabric cost represents a 13% of the total production cost. It can be concluded that, although the foam cost represents 78% of the total cost, a cost increment in the mattress is small in the CCS scenario.

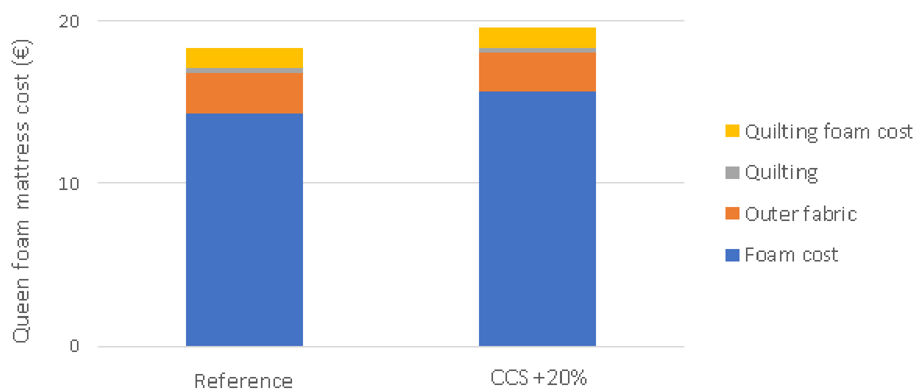



*Figure 3-11 Breakdown of mattress production cost whit and without CCS in propylene production.*

### 3.3.4.3 KEY PERFORMANCE INDICATORS

In Table 3.31 the $CO_2$ emissions indicators and the economic indicators along the value chain are presented. It can be concluded that avoiding 64% of the direct $CO_2$ emissions along the value chain by implementing CCS in propylene production has a little impact of about 7% on the mattress production cost. It should be noted that $CO_2$ emissions from propylene production are the only contributor to value chain carbon footprint).

[9] Estimated based on foam production cost and the amount of foam used per mattress. For instance, (2.7€/kg $_{foam}$)*( 10kg foam)= 27€

*Table 3.31 key performance indicators for mattress production*

| | Reference scenario | CCS scenario |
|---|---|---|
| Propylene (€/kg $_{propylene}$) | 0.85 | 1.02 |
| Increment | | 20% |
| Propylene oxide (€/kg $_{PO}$) | 0.74 | 0.88 |
| Increment | | 18% |
| Polyol (€/kg $_{polyol}$) | 0.83 | 0.96 |
| Increment | | 15% |
| Foam (€/kg $_{foam}$) | 1.4 | 1.6 |
| Increment | | 9% |
| Mattress (€/mattress) | 18 | 19.6 |
| Increment | | 7% |
| $CO_2$ avoided | | 64% |

# 4. ANALYSIS

In this section, the case studies are analyzed to provide further understanding. A sensitivity analysis is performed to evaluate economic indicators. Furthermore, adding a carbon tax in primary production is evaluated.

## 4.1 CASE STUDY I: BRIDGE

In this case study, two energy-intensive industries (e.g., cement and steel) are involved in primary production. Since cement and HRC are the only products, all the CCS cost is allocated to those products. CCS implementation in each process impacts the production cost in different magnitude. For instance, the cement production cost increases from 60% to 90% (i.e., depending on the capture technology), and the steel production cost increases by about 14%. However, only 15% of cement is used as a material to produce concrete, therefore, the concrete production cost increases by about 10%. Unlike cement, steel is used directly as a bridge construction material without the need for an intermediate. Also, the bridge construction cost increases by about 1% due to the material cost (e.g., steel and concrete) represents about 10% of the total construction cost. Additionally, CCS implementation in each process impacts the $CO_2$ emission reduction in different magnitude. For instance, 90% of the $CO_2$ emitted during cement production is avoided meanwhile in steel production about 50% of the $CO_2$ emitted is avoided.

Different scenarios combining CCS implementation in primary production are presented to analyze to what extend the increment in the production cost of each industry impacts the bridge construction cost. Additionally, to analyze to what extend the $CO_2$ emissions reduction un each industry impacts the $CO_2$ emissions along the value chain. The scenarios are presented in Table 4.1 and defined as follows:

- (R) cement and steel production without CCS.
- (C) cement production with CCS and steel production without CCS (i.e., considering different capture technologies in cement production).
- (S) steel production with CCS and cement production without CCS.
- (B) cement and steel productions with CCS.

*Table 4.1 Combination of CCS in primary production*

| **Cases** | **CCS in primary production** | |
|---|---|---|
| | **Cement** | **Steel** |
| R | ✗ | ✗ |
| B | ✓ | ✓ |
| S | ✗ | ✓ |
| C | ✓ | ✗ |

In Table 4.2the total $CO_2$ emissions along the value chain and the total construction cost for all scenarios are presented. After combining different scenarios, the results indicate that the increment in the bridge construction cost is 1% or less either CCS is implemented in cement and steel production, or if it is implemented in only one industry compared to the reference scenario without CCS. In contrast, there is a significant difference in $CO_2$ avoided emissions. For instance, scenario C (i.e., either oxyfuel or CaL capture technologies in cement production) the $CO_2$ avoided is about 46% (compared to the reference scenario). In scenario S, where CCS is implemented only in steel production, the $CO_2$ avoided is about 20% (compared to the reference scenario).

*Table 4.2 CO2 emissions and construction cost for all scenarios*

| | R | B (oxyfuel) | B (CaL) | S | C (oxyfuel) | C (CaL) |
|---|---|---|---|---|---|---|
| Total $CO_2$ emissions (kt) | 128 | 46 | 45 | 104 | 69 | 69 |
| $CO_2$ avoided [a] | | 64% | 65% | 19% | 46% | 46% |
| Total construction cost (M€) | 383 | 386 | 387 | 384 | 385 | 386 |
| Increment [a] | | 0.9% | 1.2% | 0.3% | 0.6% | 0.8% |

[a] Compared to the reference scenario

Figure 4-1 shows that the material cost represents about 10% of the total construction cost in the reference scenario (without CCS) and about 11% in the CCS scenarios. This slight increase in the material cost share is caused by an increment in the production cost of cement, concrete, and steel when CCS is implemented in primary productions (e.g., cement and steel). Therefore, it can be concluded that implementing CCS in any scenario (B), (S), and (C) has a negligible impact in the construction material cost, hence, in the total construction cost.

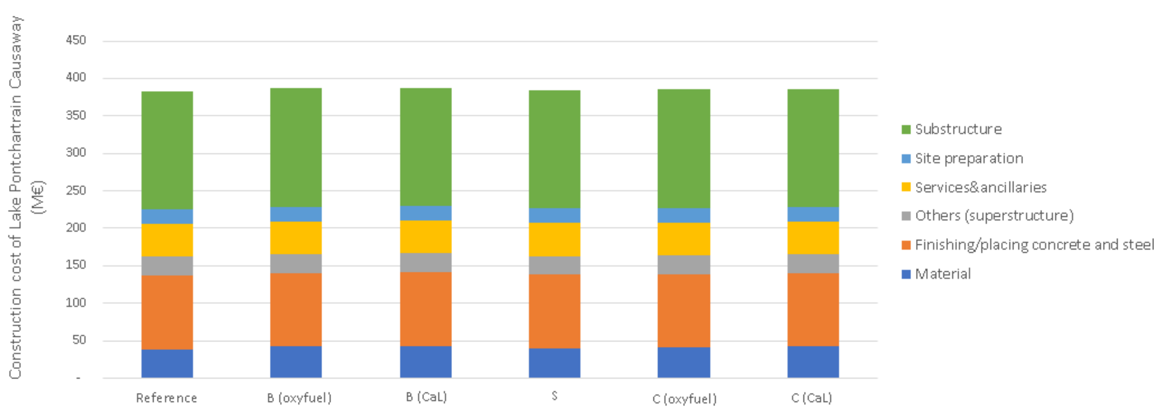



*Figure 4-1 Breakdown of the bridge construction cost for all scenarios.*

Figure 4-2 shows that direct $CO_2$ emissions from cement and steel production represents about 50% and 45% respectively of the total carbon footprint along the value chain in the reference scenario (without CCS) and together represents about 96% of the total emissions along the value chain. In (S) the $CO_2$ emissions from steel production represent about 30% of the total emissions along the value chain unlike (C) where the $CO_2$ emission from steel production represents about 80%. Therefore, it can be concluded that implementing CCS in any scenario (B), (S), and (C) has a significant impact on the carbon footprint and the $CO_2$ avoided emissions along the value chain.

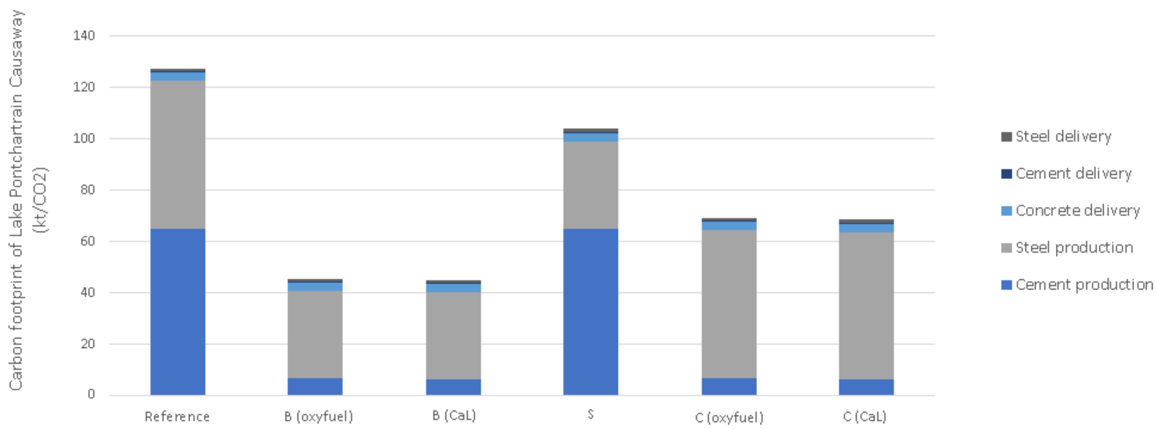



*Figure 4-2 Breakdown of the CO2 emissions along the value chain*

In can be concluded that implementing CCS in any scenario (B), (S), and (C) contributes to avoiding between 20% to 65% of the total $CO_2$ emissions along the value chain with a slight increment in the bridge construction cost of 1% or less compared to the reference scenario (without CCS). Therefore, the cost of decarbonizing the value chain from cement and steel productions to bridge construction is negligible.

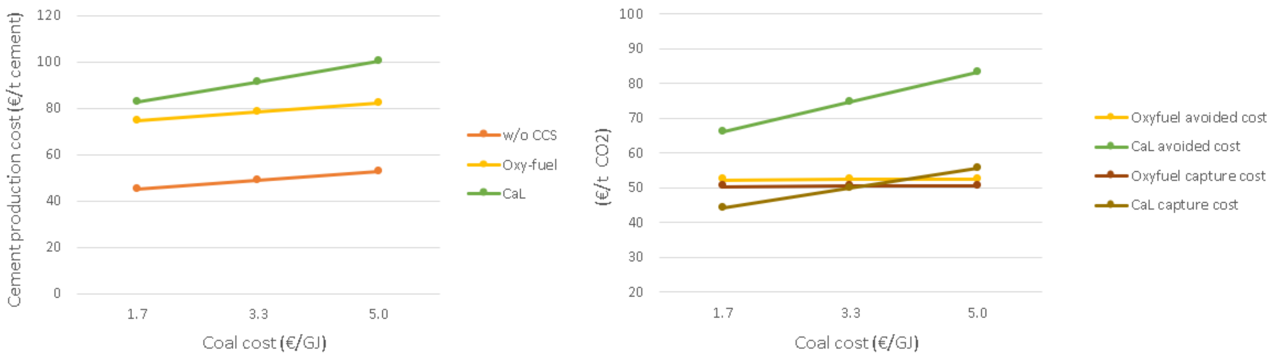
## 4.1.1 SENSITIVITY ANALYSIS

In this section a sensitivity analysis in the economic indicators are performed with cost variation as follows:

- Coal cost: +/- 50% of the cost in the reference scenario
- Electricity cost: +/- 50% of the cost in the reference scenario
- Natural gas cost: +/- 50% of the cost in the reference scenario
- CAPEX of $CO_2$ capture technologies: +35/- 15% of the CCS scenario estimate

### 4.1.1.1 CEMENT PRODUCTION

Figure 4-3 (a) presents the sensitivity of the cement production cost to the variation of coal cost. A variation in the coal cost has the highest impact on the cement production cost with CaL tail end technology since this process demands additional consumption of coal. Oxyfuel technology is affected by the cost of coal since coal is inherent consumed in the cement production process in the reference scenario (without CCS) and not due to additional demand by the capture technology. Figure 4-3 (b) presents the sensitivity of the $CO_2$ avoided cost and $CO_2$ capture cost to the variation of coal cost. A variation in the coal cost has the highest impact on the $CO_2$ avoided cost with CaL tail end technology since this process demands additional consumption of coal. Regarding oxyfuel technology, the $CO_2$ avoided cost as well as the $CO_2$ capture cost is unaffected by the cost of coal due to this technology does not demand additional consumption of coal.

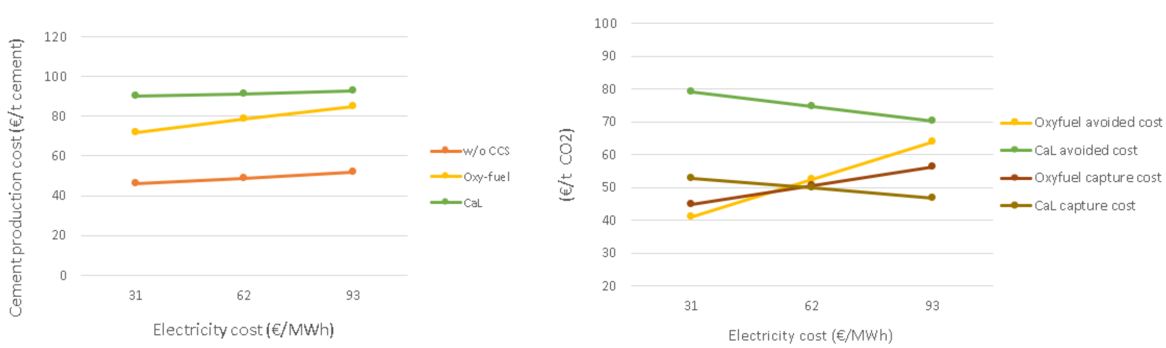



(a) (b)

*Figure 4-3 Sensitivity of the cement production cost, CO2 avoided cost, and CO2 capture cost to +/- 50% change in coal cost*

Figure 4-4 (a) presents the sensitivity of the cement production cost to the variation in electricity cost. The production cost in the CaL process is slightly affected by the electricity cost because electricity produced by the CaL process covers part of the demand for electricity in the cement production process. Oxyfuel technology is affected by the electricity cost since this capture technology relies on electricity.

Figure 4-4 (b) presents the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation in electricity cost. An increase in the electricity cost leads to a decrease in the $CO_2$ avoided cost as well as in the $CO_2$ capture cost in the CaL scenario. This can be explained because the electricity produced within the CaL process covers part of the electricity demanded by the cement production process. In contrast, the oxyfuel technology is sensitive to the variation of electricity cost increasing its $CO_2$ avoided cost and $CO_2$ capture cost.

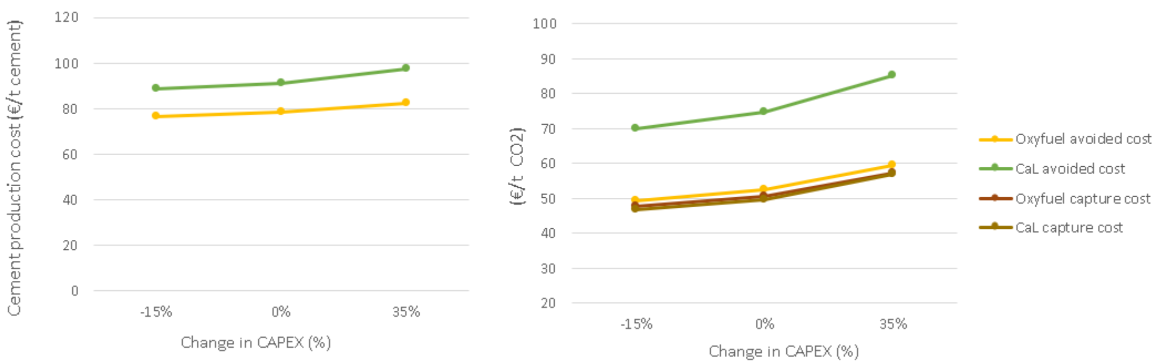



(a) (b)

*Figure 4-4 Sensitivity of the cement production cost, CO2 avoided cost, and CO2 capture cost to +/-50% change in electricity cost*

It can be concluded that a higher or lower coal cost affects the cement production cost and $CO_2$ avoided cost and $CO_2$ capture cost for the capture process that relies on coal (e.g., CaL tail end technology). In contrast, electricity-intensive technologies, such as oxyfuel, are most sensitive to a variation in electricity cost. If some electricity is produced on-site, the $CO_2$ avoided cost is lower.

Figure 4-5 (a) and (b) presents the sensitivity of the cement production cost, $CO_2$ avoided cost and $CO_2$ capture cost to the variation of CAPEX of $CO_2$ capture technologies. Both technologies are significantly affected. However, since CAPEX for the CaL process is higher than oxyfuel, the former has a higher impact on cement production cost, its $CO_2$ avoided cost, and $CO_2$ capture cost. It is worth mentioning that a change in the CAPEX also affects the fixed OPEX.



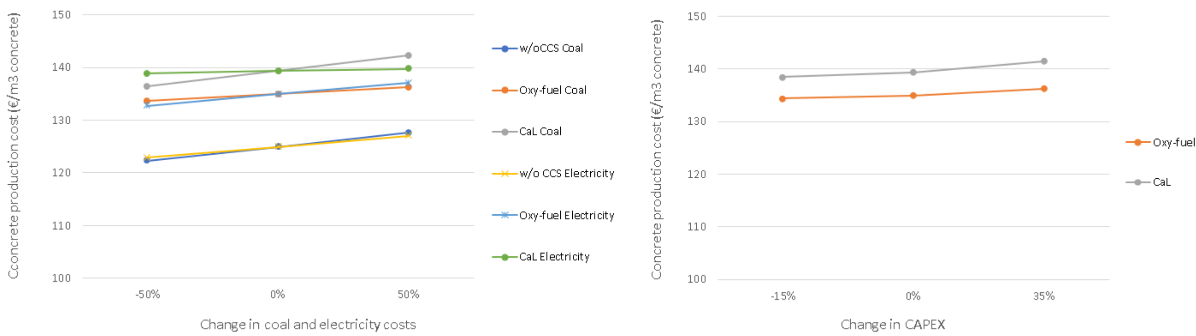

(a) (b)

*Figure 4-5 Sensitivity of the cement production cost, CO2 avoided cost and CO2 capture cost to +35%/-15% change in estimated CAPEX in the CCS scenario estimate.*

### 4.1.1.2 CONCRETE PRODUCTION

Figure 4-6 (a) shows the sensitivity of the concrete production cost to the variation of electricity and coal cost in cement production. The concrete has a slight impact on the production cost. As well as figure_ (b) shows the concrete production cost has little sensitivity to a variation in the CAPEX of capture technologies implemented in cement production.

It can be concluded that any variation in the electricity cost, coal cost, and CAPEX of capture technologies in cement production has a slight impact on the concrete production cost. This can be explained since cement cost represents a small part (i.e., between15%-24% with and without CCS) of the concrete production cost.



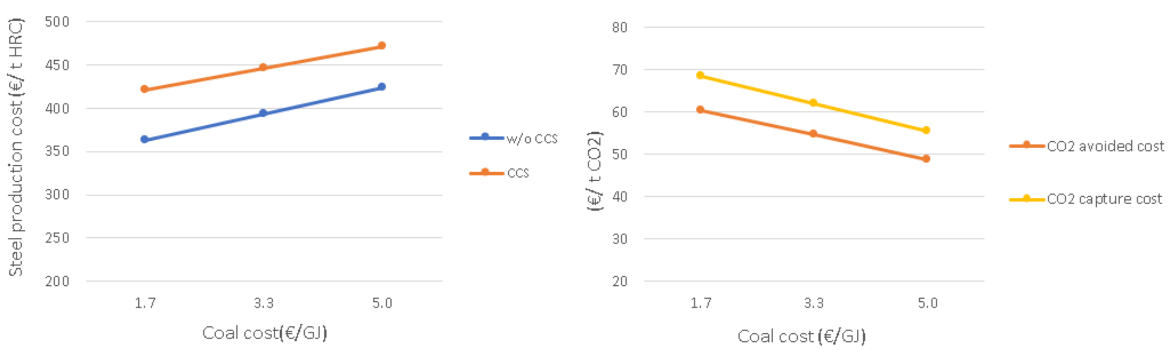

(a) (b)

*Figure 4-6 Sensitivity of the concrete production cost to +/- 50% change in electricity cost and coal cost, and to +35%/-15% change in estimated CAPEX for in cement production.*

#### 4.1.1.3 STEEL PRODUCTION

Figure 4-7 (a) shows the sensitivity of the HRC production cost to the variation of coal cost. A variation in the coal cost affects in a similar way the HRC production cost with and without CCS. This can be explained since OBF/MDEA does not require extra coal consumption to operate. Therefore, the production cost will vary since coal is used as a fuel in the steel mill plant.

Figure 4-7 (b) shows the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation of the coal cost. Although the capture technology does not consume coal an increase in the coal cost reduces the $CO_2$ avoided cost as well as the $CO_2$ capture cost since there is a reduction of coal consumption in the OBF, therefore, the direct $CO_2$ emissions generated in the steel mill are also reduced. Also, the reduction in the avoided cost is consequence of a cost reduction due to less consumed coal.

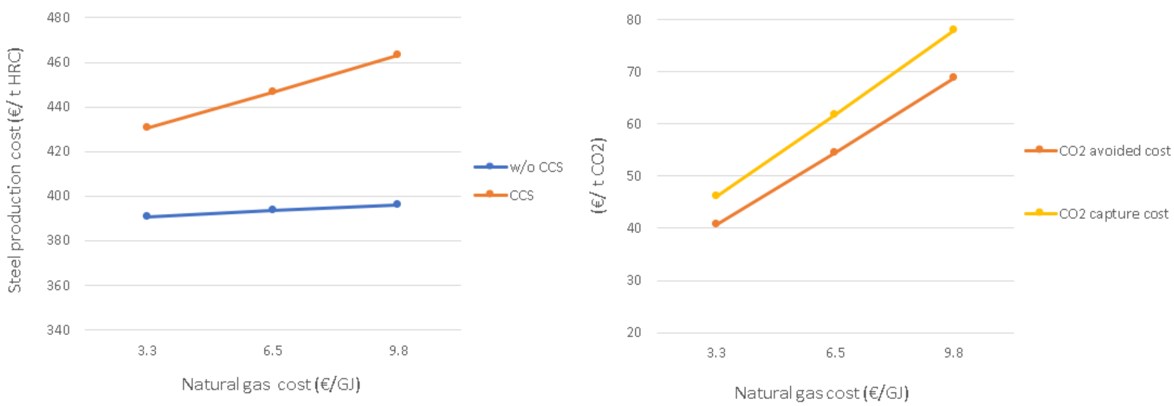



(a) (b)

*Figure 4-7 Sensitivity of the HRC production cost, CO2 avoided, and CO2 capture cost to +/- 50% change in coal cost.*

Figure 4-8 (a) shows the sensitivity of the HRC production cost to the variation of natural gas cost. OBF/MDEA is affected by natural gas costs. The capture technology requires extra demand for electricity that is produced on-site by the power plant using natural gas as fuel.

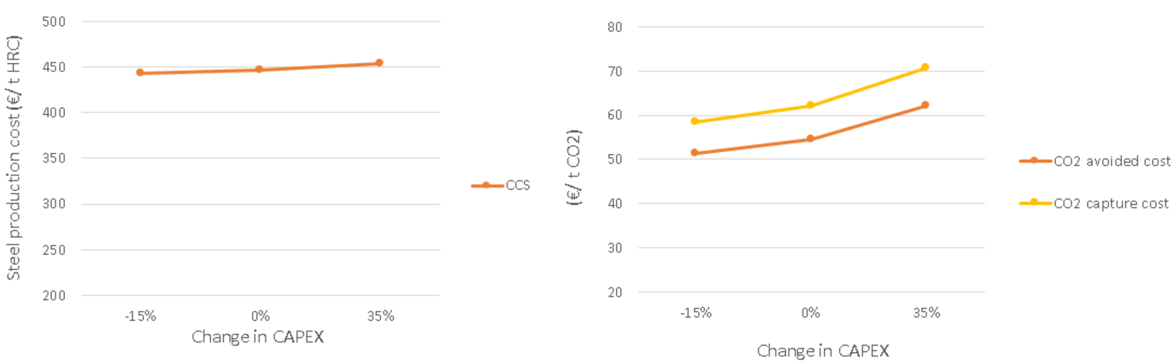
Figure 4-8 (b) shows the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation of natural gas cost. In the CCS scenario, a variation of natural gas cost increases its $CO_2$ avoided cost as well as its $CO_2$ capture cost due to the capture technology due to extra power demand.




(a) (b)

*Figure 4-8 Sensitivity of the HRC production cost, CO2 avoided cost, and CO2 capture cost to +/- 50% change in natural gas cost.*

Figure 4-9 (a) and (b) shows the sensitivity of the HRC production cost, $CO_2$ avoided cost and $CO_2$ capture cost to the variation of CAPEX of $CO_2$ capture technology. The HRC production cost with CCS is slightly changed by a variation in CAPEX. However, it has a higher impact on the $CO_2$ avoided cost.




(a) (b)

*Figure 4-9 Sensitivity of the HRC production cost, CO2 avoided cost and CO2 capture cost to +35%/- 15% change in estimated CAPEX in the CCS scenario estimate.*

#### 4.1.1.4 BRIDGE

Figure 4-10 shows the sensitivity of the bridge production cost to the variation of coal, electricity cost, and natural gas cost, in cement and steel productions. The bridge construction cost has little sensitivity to a variation in coal cost, electricity cost, and natural gas costs in primary productions with and without CCS. It should be noted that the bridge construction cost varies by about +/- 2%.

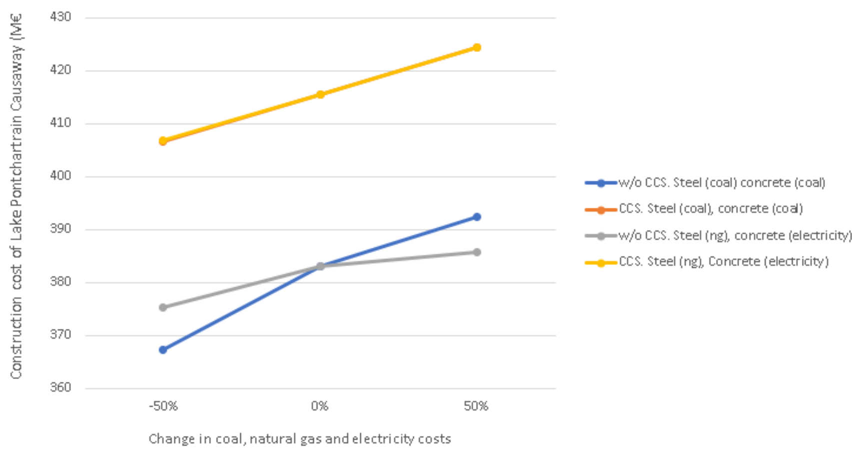



*Figure 4-10 Sensitivity of the bridge construction cost to +/- 50% change in coal, electricity cost and natural gas cost, in cement and steel productions*

## 4.2 CASE STUDY II: CORN

In this case study ammonia is defined as a primary product and urea as an intermediate product. Since urea production is integrated into ammonia facilities the production cost is expressed per tonne of urea. For the results presented in section 4.2.1 and the sensitivity analysis presented in section 5.2.1 it is assumed that in the reference scenario (without CCS) 95% of the ammonia produced is converted into urea (i.e., 5% of the produced ammonia is considered as a co-product). In the CCS scenario it is assumed 100% of the ammonia produced and 13% of the $CO_2$ captured are converted into urea (i.e., increasing the urea production). This means that ammonia as a co-product is nonexistence, therefore, CCS cost is fully allocated to the ammonia that is converted into urea and, in turn, to the urea production.

An alternative CCS scenario where 95% of the ammonia is converted into urea is presented to analyze how the CCS cost should be allocated. It should be noted that in this alternative scenario there is not an increase in the urea production compared to the reference scenario without CCS (i.e., not all ammonia is converted into urea as well as none of the $CO_2$ captured is used in urea production). Ammonia and urea can be categorized as joint products[10] of the ammonia/urea integrated plant. Therefore, the CCS cost can be considered as a joint cost[11]

[10] When a production process yields two or more products with high commercial value (Deevski, 2016)

[11] Common cost up to the point where two or more products become separately identifiable (Deevski, 2016)

The production process in the integrated ammonia/urea plant is categorized into three different phases; syngas production, ammonia synthesis, and urea production (see section 3.2.1). It is worth mentioning that the capture unit (i.e., in the CCS scenario) is installed in the primary reformer, therefore, the $CO_2$ captured comes from the syngas production phase. Then, syngas is used in ammonia synthesis, in turn, ammonia is converted to urea. Therefore, the CCS cost should be allocated to ammonia production. Since only the ammonia production cost is unknown, it is difficult to determine to what extend the ammonia production cost should increase as a consequence of implementing CCS. However, it is known that 95% of the produced ammonia is converted into urea, then 95% of the CCS cost is transferred to urea production. Also, to produce one tonne of urea 0.57 tonne of ammonia is required (0.57 $t_{NH3}/t_{urea}$). Therefore, a backward estimation with simple relations can be performed based on the results in section 4.2.1.3. It was concluded in the economic assessment that the urea production cost increases by 6% as a consequence of implementing CCS. The relation is as follows: $\frac{6\%}{t_{urea}} * \frac{t_{urea}}{0.57\ t_{NH3}} = 10.5\%$

That value of 10.5% represents the increment in the ammonia production cost. However, this corresponds to 95% of the ammonia produced. This means that 100% of the ammonia produced the production cost increases by 11%.

It can be concluded that implementing CCS in ammonia production leads to an increment in the production cost per tonne of ammonia by about 11%. Since 0.57 tonne of ammonia is used to produce urea, the urea production cost per tonne of urea increases by 6%. Afterward, urea is used as fertilizer in a corn crop increasing its operating cost per acre by 3%. This can be explained due to fertilizer cost represents 53% of the total operating cost. Therefore, the cost of decarbonizing the value chain from ammonia production to the corn crop by reducing about 90% of the $CO_2$ emissions is negligible.

## 4.2.1 SENSITIVITY ANALYSIS

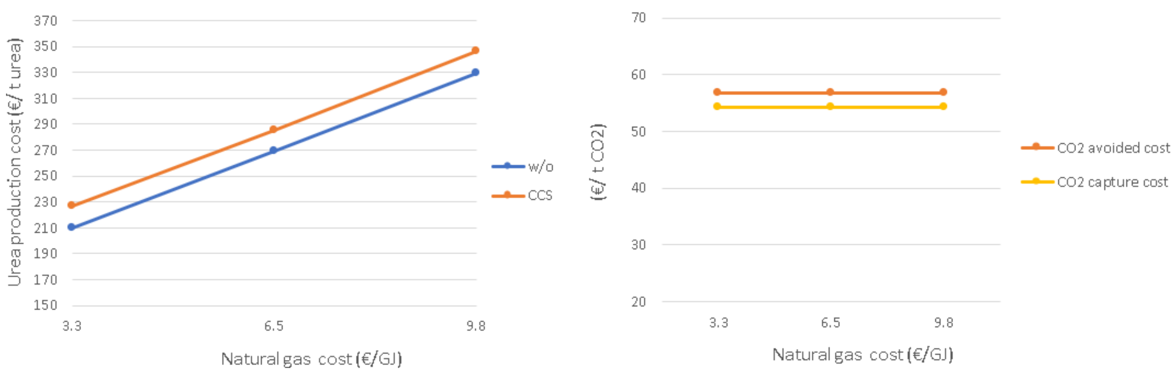
In this section a sensitivity analysis in the economic indicators are performed with cost variation as follows:

- Electricity cost: +/- 50% of the cost in the reference scenario
- Natural gas cost: +/- 50% of the cost in the reference scenario
- CAPEX of $CO_2$ capture technologies: +35/- 15% of the CCS scenario estimate

### 4.2.1.1 AMMONIA/UREA PRODUCTION

Figure 4-11 (a) shows the sensitivity of the urea production cost to the variation of natural gas cost. The variation in the natural gas cost affects similarly the urea production cost in the reference scenario and the CCS scenario. This can be explained since the capture technology does not require extra natural gas consumption to operate. Therefore, the production cost will vary since natural gas is used as a feedstock as well as fuel in the ammonia synthesis.

Figure 4-11 (b) shows the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation of natural gas cost. The $CO_2$ avoided cost as well as the $CO_2$ capture cost is unaffected by a variation in the natural gas cost due to the capture unit increased the electricity demand instead of natural gas demand.

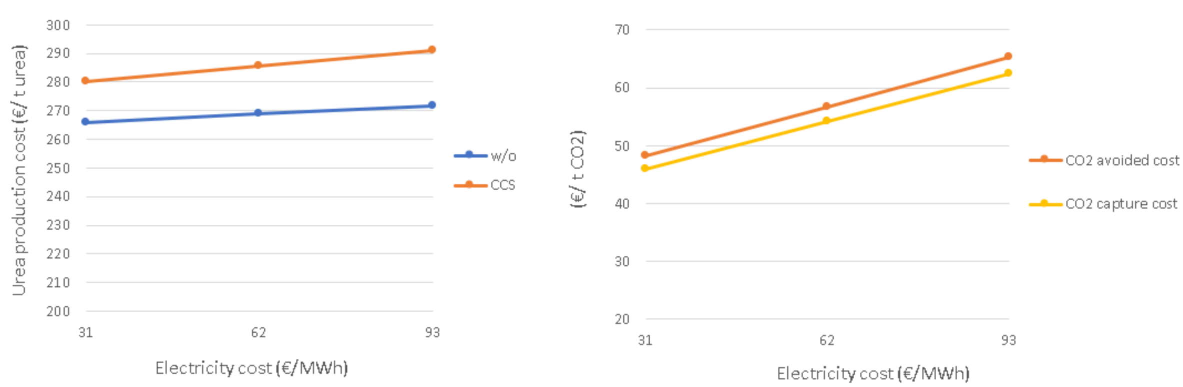



(a) (b)

*Figure 4-11 Sensitivity of the urea production cost, CO2 avoided cost, and CO2 capture cost to +/-50% change in natural gas cost.*

Figure 4-12 (a) shows the sensitivity of the urea production cost to the variation of electricity cost. The production cost in the CCS scenario is slightly affected by the electricity cost even when the electricity demand is higher compared to the reference scenario. This can be explained since electricity cost represents 2% of the total production cost in the CCS scenario.

Figure 4-12 (b) shows the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation in electricity cost. The $CO_2$ avoided cost, as well as the $CO_2$ capture cost, are sensitive to a variation in the electricity cost since the capture process demands additional consumption of electricity.




(a) (b)

*Figure 4-12 Sensitivity of the urea production cost, CO2 avoided cost, and CO2 capture cost to +/-50% change in electricity cost.*

It can be concluded that a variation in electricity cost slightly affects the production cost, however, the $CO_2$ avoided cost and capture cost are more sensitive to that since the capture technology relies on electricity. In contrast, the $CO_2$ avoided cost is unaffected by a variation in natural gas cost

Figure 4-13 (a) and (b) shows the sensitivity of the urea production cost and $CO_2$ avoided cost to the variation of CAPEX of $CO_2$ capture technology. The urea production cost with CCS is slightly changed by a variation in CAPEX. However, it has a higher impact on the $CO_2$ avoided cost.

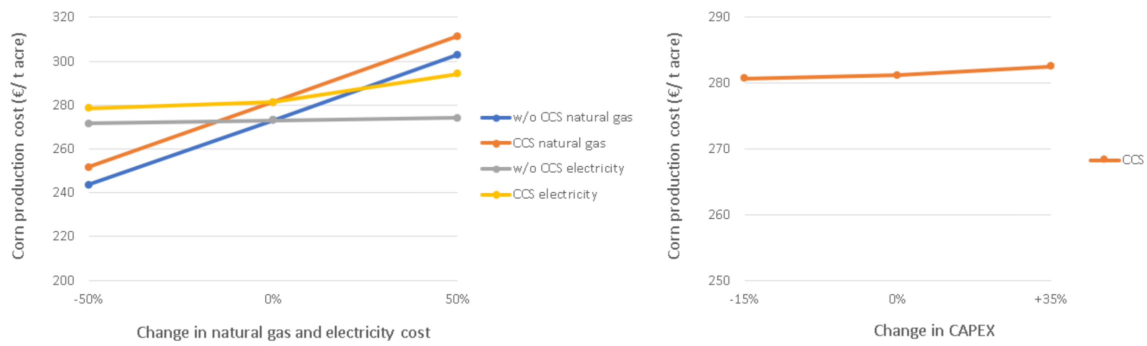

(a) (b)

*Figure 4-13 Sensitivity of the urea production cost, CO2 avoided cost, and CO2 capture cost to +35%/-15% change in estimated CAPEX in the CCS scenario estimate.*

### 4.2.1.2 CORN

Figure 4-14 (a) shows the sensitivity of the corn production cost to the variation of electricity and natural gas costs in urea production. The production cost of corn has little sensitivity to a variation in the electricity cost in urea production cost with and without CCS. In contrast, a variation in the natural gas cost in urea production in both scenarios has a considerable impact on the corn production cost. This can be explained since natural gas is used as a feedstock and fuel in urea production. Figure 4-14 (b) shows that the corn production cost has little sensitivity to a variation in the CAPEX of the capture technology implemented in ammonia/urea production.

It can be concluded that any variation in the electricity cost and CAPEX of capture technology in urea production has a slight impact on the corn production cost even when the fertilizer cost (e.g., urea) represents 50% of the corn production cost. In contrast, a variation in the natural gas cost in urea production has a considerable impact on the corn production cost.




(a) (b)

*Figure 4-14 Sensitivity of the corn production cost to +/- 50% change in electricity cost and natural gas cost, and to +35%/-15% change in estimated CAPEX in urea production.*

# 4.3 CASE STUDY III:

In this case study, the production cost is estimated differently. In an oil refinery, the cost of crude and the product prices are required to estimate the optimum product yield (IEAGHG, 2017c). However, to estimate the refinery processing cost (i.e., processing cost per oil barrel) the cost of the feedstock (e.g., crude oil and imported vacuum gasoil) is not required (IEAGHG, 2017c). For instance, if the processing cost (e.g., annualized CAPEX and annual OPEX) is divided into the annual production of each product (e.g., propylene, gasoline, diesel) all products have the same production cost which is not correct. Therefore, unlike the other case studies, the production cost is not expressed per tonne of product (e.g., €/$t_{propylene}$). Instead, the annual refinery processing cost (e.g., annualized CAPEX and annual OPEX) is reported.

Unlike the other case studies, an oil refinery plant yields multiple products with different commercial values. Because of that, along with the complexity of the refining process, the cost allocation of CCS represents a challenge.

There are two cost allocation approaches; mass-based and energy-based (see methodology). Within those approaches there are two different methods; (a) the CCS cost is allocated in the product streams (e.g., propylene, gasoline, diesel), and (b) the CCS cost is allocated in the process streams (e.g., an outlet stream from CDU unit that goes to the VDU unit) considering only the streams and the units related to propylene production. Also, each approach leads to a significantly different result. For instance, (a) allocates 1% of the CCS cost to propylene and (b) allocates 2% of the CCS cost. Besides, the percentage of allocation cost provided by mass-based and energy-based presents a negligible difference.

It can be concluded that the CCS cost that is allocated based on process streams (a) is double compared to the product streams (b). Due to the complexity of the refining process the process streams approach (a) (i.e., either mass-based or energy-based) suggests a more precise allocation of costs. However, to confirm that statement a more complex estimation along all the process streams and units would be required (i.e., process modeling or solving a linear model). It can be concluded that the refinery processing cost increases by 20% when CCS is implemented in the oil refinery avoiding 64% of the direct emissions.

### 4.3.1 SENSITIVITY ANALYSIS

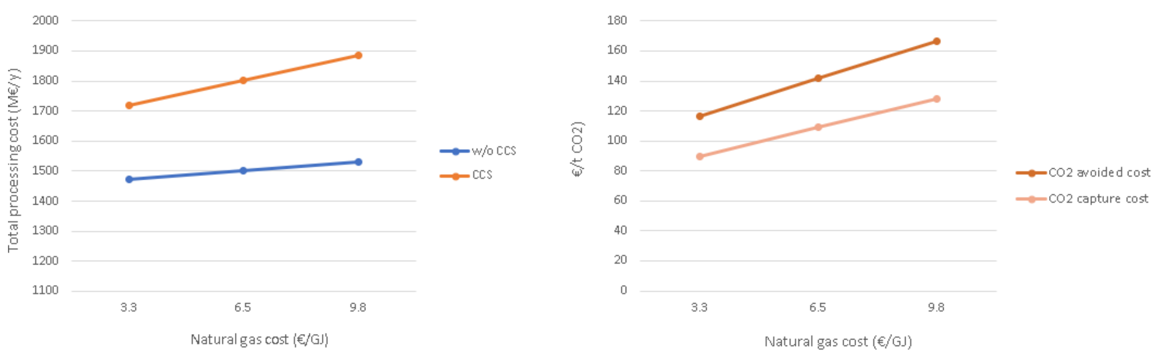
In this section a sensitivity analysis in the economic indicators are performed with cost variation as follows:

- Natural gas cost: +/- 50% of the cost in the reference scenario
- CAPEX of $CO_2$ capture technologies: +35/- 15% of the CCS scenario estimate

#### 4.3.1.1 OIL REFINERY PROCESSING COST

Figure 4-15 (a) shows the sensitivity of the oil refinery processing cost to the variation of natural gas cost. A variation in the natural gas cost has a higher impact on the processing cost with CCS since the capture process demands additional consumption of natural gas to the generation of power and steam.

Figure 4-15 (b) shows the sensitivity of the $CO_2$ avoided cost and the $CO_2$ capture cost to the variation of natural gas cost. A variation in the natural gas cost has a significant impact on the $CO_2$ avoided cost as well as in the $CO_2$ capture cost due to the additional consumption of natural gas by the capture and compression unit.

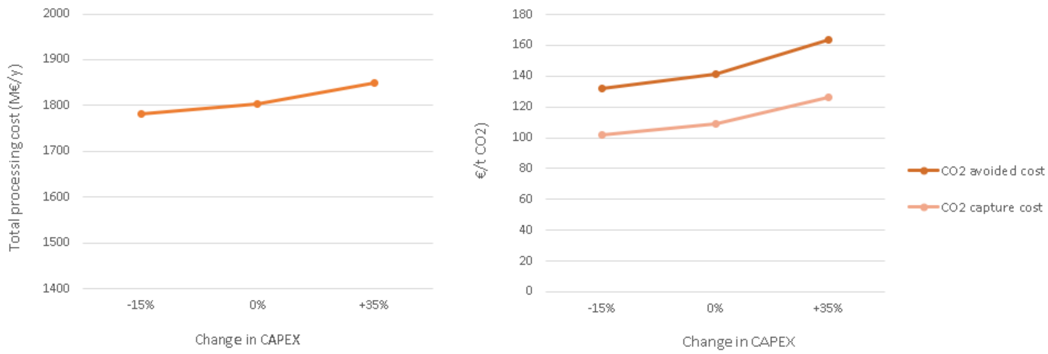



(b) (b)

*Figure 4-15 Sensitivity of the oil refinery processing cost, CO2 avoided cost, and CO2 capture cost to +/- 50% change in natural gas cost.*

It can be concluded that a variation in natural gas cost slightly affects the production cost without CCS, however, the $CO_2$ avoided cost and capture cost are more sensitive to that since the capture process requires more natural gas.

Figure 4-16 (a) and (b) shows the sensitivity of the oil refinery processing cost, $CO_2$ avoided cost, and $CO_2$ capture cost to the variation of CAPEX of $CO_2$ capture technology. The oil refinery processing cost with CCS has slightly changed by a variation in CAPEX. However, it has a higher impact in the $CO_2$ avoided cost as well in the $CO_2$ capture cost.

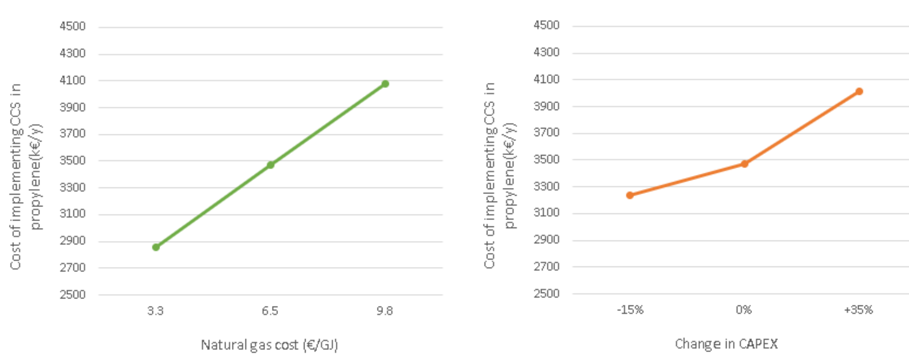



(a) (b)

*Figure 4-16 Sensitivity of the oil refinery processing cost, CO2 avoided cost, and CO2 capture cost to +35%/-15% change in estimated CAPEX in the CCS scenario estimate.*

### 4.3.1.2 CCS COST ALLOCATION IN PROPYLENE PRODUCTION

Figure 4-17 (a) and (b) shows the sensitivity of the CCS implementation cost allocated to propylene considering the mass-based allocation approach using product streams (see section 4.3.1.2.1) to the variation of natural gas and CAPEX of $CO_2$ capture technology. Since the cost of implementing CCS in the oil refinery is sensitive to a variation in natural gas cost and CAPEX, the share of this cost that is allocated to propylene production is also sensitive to any variation in natural gas cost and CAPEX. It means that the higher the natural gas cost the higher cost allocated to propylene.




(b) (b)

*Figure 4-17 Sensitivity of the cost of implementing CCS allocated (mass-based) to propylene to natural gas oil refinery processing cost, CO2 avoided cost, and CO2 capture cost to +/- 50% change in natural gas cost and +35%/-15% change in estimated CAPEX in the CCS*

### 4.3.1.3 PROPYLENE OXIDE, POLYOL, FOAM, AND MATTRESS

Figure 4-18 shows the sensitivity of the polyol, foam, and mattress production cost to the variation of natural gas cost in propylene production with CCS. The impact in the polyol, foam, and mattress production cost due to a variation in the natural gas in the oil refinery with CCS is neglectable.

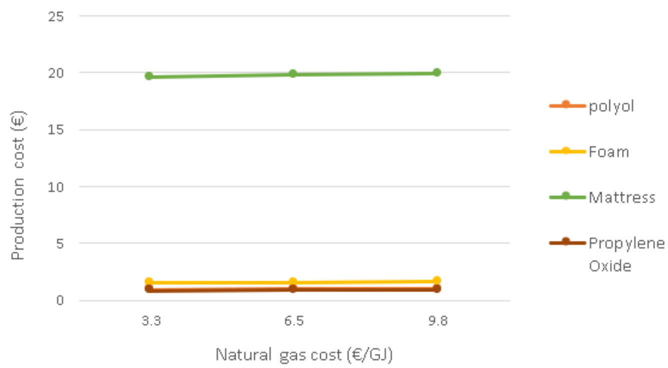



*Figure 4-18 Sensitivity of the propylene oxide, polyol, foam, and mattress production costs to +/- 50% change in natural gas cost in propylene production with CCS.*

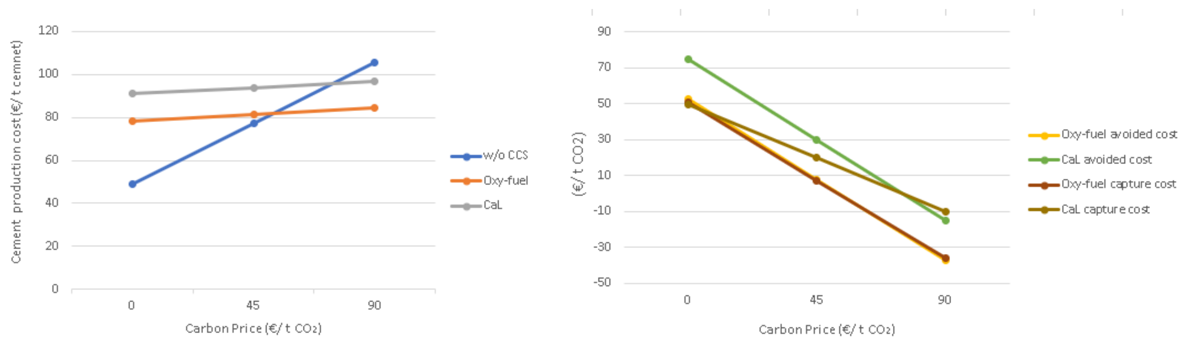
## 4.4 CARBON TAX

Figure 4-19 shows the production cost, $CO_2$ avoided and $CO_2$ capture cost of each case study when a carbon tax is implemented. Implementing a carbon tax has a significant impact leading to a considerable increase in the primary production cost without CCS. For instance, with a carbon tax of 45€/$t_{CO2}$, the production cost with CCS is still higher than the production cost in the reference scenarios. Although, at this carbon price, the primary production cost with CCS is slightly higher than the production cost in the reference scenarios (except in the oil refinery) a higher carbon tax is required to make the production cost with CCS lower than the reference scenarios without CCS and, in turn, encourage the CCS implementation in the industrial processes.

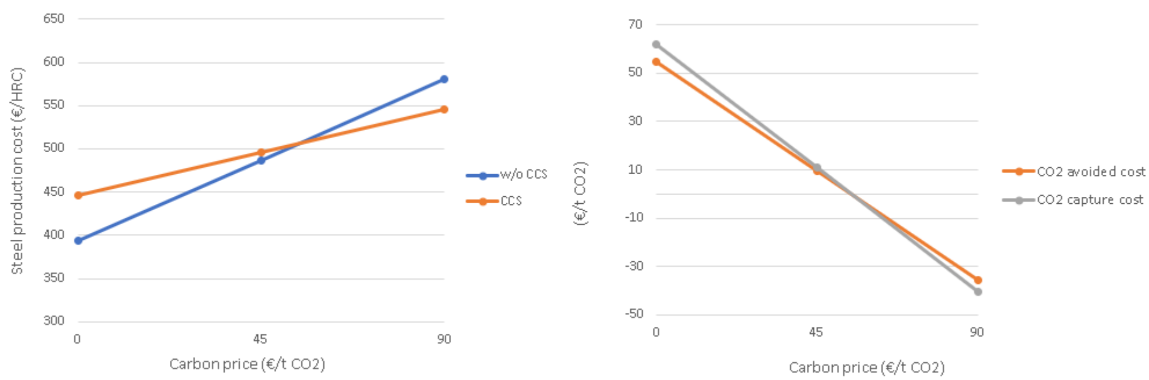
According to Simbeck & Beecy, 2011 the $CO_2$ avoidance cost is the carbon tax value at which the production costs with and without CCS are the same. Therefore, from that value, CCS is economically viable in terms of production costs. It is worth mentioning that there is an important difference between the $CO_2$ avoided cost and capture cost concepts. The former is estimated based on the emission reduction or avoidance to the atmosphere. The latter is estimated based on the amount of $CO_2$ captured. Since CCS is considered a measure to reduce the $CO_2$ emissions that are released into the atmosphere the $CO_2$ avoided cost should be used to discuss the carbon tax value (Simbeck & Beecy, 2011).

As can be seen from the $CO_2$ avoided costs and production cost in figure_ at carbon tax value higher than 55€/$t_{CO2}$ the production cost with and without CCS are the same, except in the oil refinery in which a carbon price higher than 100 €/$t_{CO2}$ is required.

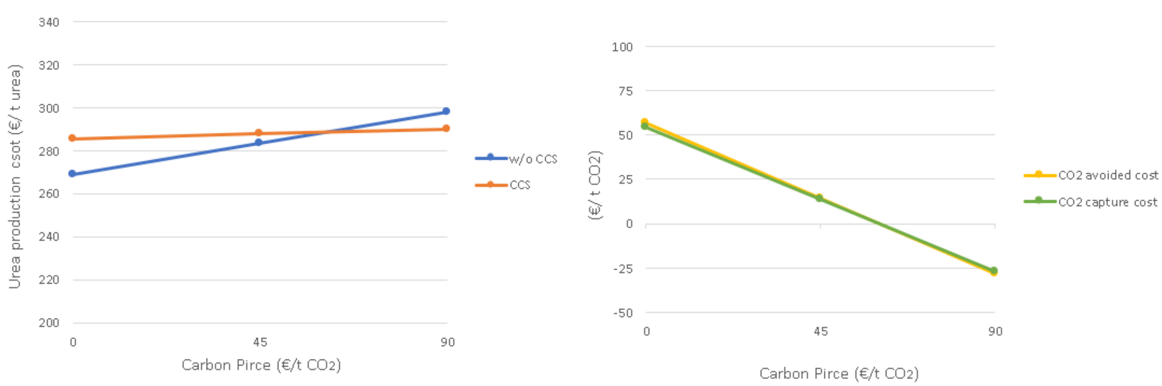
It can be concluded that the same carbon tax value would have a different impact on the production cost with and without CCS. This can be explained due to the type of process as well as the type of capture technology. For instance, to have a lower production cost with CCS in the cement production a carbon tax of about 55€/$t_{CO2}$ in oxyfuel is required while with CaL technology is about 70€ /$t_{CO2}$.



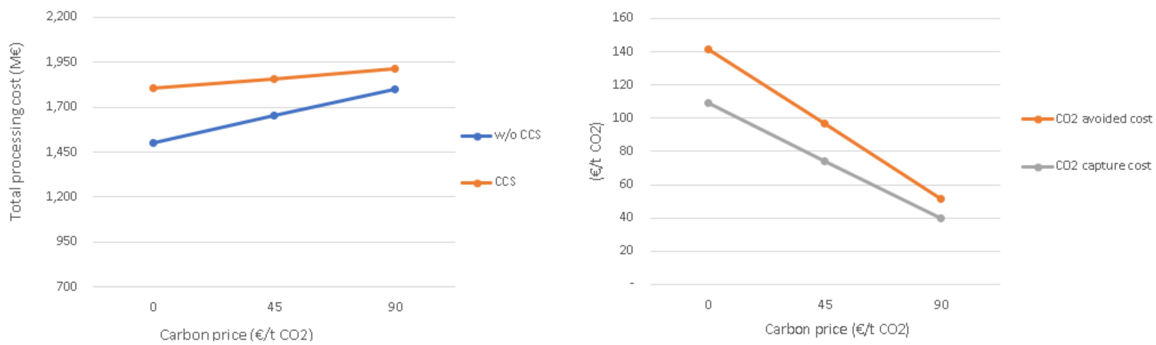

(a)




(b)




( c)




(d)

*Figure 4-19 Production cost, CO2 avoided and CO2 capture cost of (a) cement production, (b) steel production, (c) urea production, (d) oil refinery processing when a carbon tax is implemented.*

## 4.5 KEY PERFORMANCE INDICATORS IN PRIMARY PRODUCTION

The key performance indicators are divided into carbon footprint indicators (e.g., $CO_2$ capture ratio and $CO_2$ avoided) and economic indicators (e.g., production cost, $CO_2$ avoided cost and $CO_2$ capture cost).

Table 4.3 presents the key performance indicators for all industries. It should be noted that for cement, steel, and ammonia/urea production the $CO_2$ emissions are expressed as specific emissions (i.e., per tonne of product). Those values were converted to annual emissions to standardize and compare $CO_2$ emissions with the oil refinery plant (i.e., emissions are not given per tonne of product). The $CO_2$ capture cost and the avoided cost are different in each industry even when the costs are expressed per tonne of $CO_2$. Those costs are estimated based on the production cost, and, the production cost depends on the type of industry and type of products as well as the direct $CO_2$ emissions related to its production process. For instance, the cost of producing one tonne of cement is not the same as the cost of producing one tonne of steel. Also, the number of direct emissions that are generated in each process is different. Therefore, either avoiding one tonne of $CO_2$ or capturing one tonne of $CO_2$ has a different cost for each type of industry.

$CO_2$ avoided cost represents the cost of reducing the $CO_2$ emissions that are released into the atmosphere. It is also considered the cost to society of reducing emissions (IPCC, 2005a). In this case, the $CO_2$ avoided cost is the cost to the industry of reducing or avoiding its released emissions while the production does not change. Also, the avoided cost per tonne of $CO_2$ represents the cost of switching to a decarbonized process. For instance, avoiding 90% of the direct emissions in the cement industry leads to an increment in the production cost between 60-90% compared to an increment in the urea production cost of 6% in which also 90% of the emissions are avoided.

The capture cost represents the cost of capturing one tonne of $CO_2$ while the production does not change (IPCC, 2005a). For instance, Also, the capture cost represents the economic viability of capture emissions if the $CO_2$ capture is sold as a commercial product to the market (IPCC, 2005a). If the $CO_2$ is sold at the capture cost, the production cost with and without CCS should be the same (IPCC, 2005a). In this thesis, the capture $CO_2$ is transported and stored rather than selling to other industries.

*Table 4.3 KPIs for all the case studies*

| KPI's | Cement | | Steel | Ammonia/urea | Oil refinery |
|---|---|---|---|---|---|
| | Oxyfuel | CaL | | | |
| $CO_2$ emissions without CCS (kt/y) [a] | 852 | | 8360 | 245 | 3351 |
| $CO_2$ emissions with CCS (kt/y) [a] | 88 | 79 | 4459 | 25 | 1220 |
| $CO_2$ captured (kt/y) | 794 | 1158 | 3444 | 230 | 2769 |
| $CO_2$ capture cost (€/$t_{CO2}$) | 51 | 50 | 54 | 54 | 109 |
| $CO_2$ avoided | 90% | 91% | 47% | 90% | 54% |
| $CO_2$ avoided cost (€/$t_{CO2}$) | 53 | 75 | 57 | 57 | 142 |
| Increase production cost [b] | 60% | 90% | 14% | 6% | 20% |

[a] Specific $CO_2$ emissions per tonne of product multiplied by the annual production
[b] Compared to the production cost in the reference scenario without CCS

# 5. DISCUSSION

In this section, the results from section 3 and the analysis in section 4 are discussed to answer the sub-questions. Also, the limitation of the research is discussed.

## 5.1 KEY TECHNICAL FACTORS

To estimate and evaluate the performance indicators some technical factors were selected. The sub-question $Q_1$ refers to the relevance of the technical factors selected to perform the carbon footprint and economic estimations.

*$Q_1$: What are the key technical factors that influence final product costs and their $CO_2$ emission reduction when CCS is implemented in the production of industrial products?*

The technical factors required to estimate KPIs in primary production are presented.

1. $CO_2$ captured and the $CO_2$ avoided: production capacity, type of production process, type of fuel (e.g., natural gas, coal), electricity (i.e., generated on-site or imported from the grid to determine if it accounts as direct or indirect emissions), and capture technology.

2. Production cost: production capacity and type of production process to estimate the operating cost and the capital cost.

3. Capture cost and the $CO_2$ avoided cost: capture technology, production cost, amount of $CO_2$ captured, and amount of $CO_2$ avoided based on the $CO_2$ emitted before capture.

In this research, the final product cost is evaluated through a value chain where CCS is implemented in primary production. Therefore, the technical factors that influence the primary product cost with and without CCS are discussed first.

Although the production capacity and the type of production process influences the production cost, those factors can be seen as the characteristics to define the reference plant in which the production cost is estimated with and without CCS. To provide deeper insight into production cost, the breakdown of the production cost into its main cost factors (e.g., variable OPEX, fixed OPEX, and CAPEX) is analyzed.

In cement production cost, the main contributor is the variable OPEX representing about 40% of the total production cost in the reference and CCS scenarios. In the variable OPEX, the main contributors are the fuel cost (e.g., coal) representing 16% and the electricity cost (i.e., imported from the grid) representing 12% of the total production cost in the reference scenario. CAPEX represents 32% of the total production cost. In the oxyfuel scenario, the breakdown into its main cost factors is as following; coal 10%, electricity 16%, $CO_2$ transport, and storage cost 7%, and CAPEX 34% of the total production cost. In the CaL scenario, the breakdown into its main cost factors is as following; coal 19%, electricity 3%, $CO_2$ transport, and storage cost 9%, and CAPEX 36% of the total production cost.

In steel production cost, the main contributor is the variable OPEX representing about 46% of the total production cost in the reference and CCS scenarios. In the variable OPEX, the main contributors are the fuel cost (e.g., coal) representing 16%, the natural gas cost (i.e., used as fuel to produce electricity on-site) representing 12%, and the cost of the raw materials representing 26% of the total production cost in the reference scenario. CAPEX represents 28% of the total production cost. In the CCS scenario, the breakdown into its main cost factors is as following; coal 11%, natural gas 16%, $CO_2$ transport, and storage cost 2%, and CAPEX 29% of the total production cost.

In ammonia/urea production cost, the main contributor is the variable OPEX representing about 47% of the total production cost in the reference and CCS scenarios. In the variable OPEX, the main contributors are the raw material cost (e.g., natural gas) representing 2%, the fuel cost (e.g., natural gas) representing 12%, and the electricity cost representing 2% of the total production cost in the reference scenario. CAPEX represents 41% of the total production cost. In the CCS scenario, the breakdown into its main cost factors is as following; natural gas as fuel 11%, electricity cost 4%, and the $CO_2$ transport and storage cost 1% and CAPEX 41% of the total production cost.

In propylene production cost, the main contributor is the CAPEX representing about 55% of the total production cost in the reference and CCS scenario, followed by the fixed OPEX, and finally the variable OPEX. In the variable OPEX, the main contributors are the chemicals and catalysts representing 14% of the total production cost and the fuel cost (e.g., natural gas) representing 4% of the total production cost in the reference scenario. In the CCS scenario, the breakdown into its main cost factors is as following; the chemicals and catalysts cost remains unchanged, natural gas as fuel 9%, the $CO_2$ transport and storage cost 2%, and CAPEX 54% of the total production cost.

It should be noted that the CAPEX for the CCS scenario mentioned above consists of the CAPEX without CCS and the CCS investment cost. Therefore, the CAPEX value related only to the CCS investment represents a smaller percentage of the total production cost. It can be concluded that the key technical factors that influence the primary production cost when CCS is implemented are either the fuel or the electricity that is consumed by the capture unit. In cement production with oxy-fuel, the key technical factor is the electricity consumption and, in turn, its cost. In cement production with the CaL process, the key technical factor is coal consumption and, in turn, its cost. In ammonia/urea production the key technical factor is the electricity demand even when it represents a smaller portion of the total production cost compared to the natural gas used as fuel. This can be explained since the natural gas consumption remains unchanged due to CCS implementation (i.e., the capture unit increases the electricity demand). In propylene production, the key technical factor is the natural gas demand by the power plant to generate steam and electricity on-site and satisfy the capture unit demand.

Another technical factor related to CCS implementation is $CO_2$ transport and storage cost. It should be noted that for all industries this cost represents a very small or negligible fraction of the total production cost. Therefore, $CO_2$ transport and storage cost does not have a strong influence on the production cost with CCS is implemented.

Since the primary product is used as a material in the intermediate product and, in turn, in the final product, the key technical factors that influence the primary production cost with CCS also influence the final product cost. However, the impact on the final production cost is less than the impact on the primary production cost. For instance, based on the results provided by the sensitivity analysis if the electricity cost is higher y about 50% the cement production cost with oxy-fuel increases by about 8%. If the natural gas cost is higher by about 50% the steel production cost with CCS increases by about 4%. As a consequence, the bridge construction cost increases by about 2%. The urea production cost increases by about 2% and the corn production cost by about 1% when electricity cost increases by about 50% in the primary production. The propylene processing cost increases by about 5% and the mattress production cost by about 1% when the natural gas cost is higher by about 50% in the oil refining process. It can be concluded that even when the natural gas and electricity cost drastically increases in primary production, it has a small or negligible impact on the final production cost. This can be explained due to the cost increment in primary production cost is dragged through the value chain with a smaller impact at each stage of the value chain.

Another factor that influences the final product cost is the number of elements in the value chain and the fraction or contribution of the primary product cost as material cost in the final product cost. For instance, cement is the primary product with the highest increment in its cost by about 60-90%. However, bridge construction with CCS is higher by about 1% due to the material cost (e.g., concrete cost and steel cost) represents 10% of the total construction cost. In propylene production cost, the cost increment is dragged through several intermediate products diminishing the cost impact in each stage. For instance, from a higher propylene processing cost by about 20% to 18% in PO, 15% in polyol, 9% in foam, and 7% in the mattress.

### 5.1.1 LIMITATIONS

In this research, the $CO_2$ emissions are estimated under scope 1 (i.e., direct emissions including energy-related and process emissions). The analysis of indirect emissions (e.g., electricity imported from the grid) would provide further insight into $CO_2$ avoided and, in turn, $CO_2$ avoided cost.

The industries where electricity is generated on-site (e.g., steel and oil refinery utilizing post-combustion amine based capture technologies) did not consider revenues from exporting electricity to the grid. In these cases, electricity could be considered as a by-product to be sold with an impact on the production cost, capture cost and $CO_2$ avoided cost.

The system boundaries of the case studies were defined based on a gate-to-gate perspective. The case studies did not consider $CO_2$ emissions and costs related to the extraction and transport of raw materials that are delivered at the primary producer gate. Also, the $CO_2$ emissions related to the manufacture of the final product (i.e., emissions during bridge construction, emissions from tractors in the corn crop, and the emission during the manufacture of mattress) were not considered. Expanding the system boundaries (e.g., cradle to grave) would provide further insight into a complete value chain.

In this research, a simplified ammonia/urea production plant was assessed. In this reference, the plant did not consider the production of by-products. Typically, the fertilizer industry produces several products such as nitric acid and ammonium nitrate. Analyzing an industrial complex where ammonia is converted into several products would provide more realistic insight into the fertilizer industry.

Oil refinery production costs did not consider the raw material cost (e.g., crude price) and market prices of the products. A complex model would provide insight into an accurate propylene production cost.

## 5.2 CCS COST ALLOCATION

To assess the impact of CCS cost in primary products the CCS cost is allocated into the primary products. The sub-question $Q_2$ refers to the relevance of CCS cost allocation.

*$Q_2$: To what extent do cost allocation approaches impact the CCS cost across the value chain?*

The allocation of CCS costs in the primary product depends on whether the production process yields a single main product or also a by-product. In the cement and steel industries, only one product (e.g., cement and hot roll coil) is produced in its facilities. Therefore, the CCS cost is fully allocated to the only product that the primary production yield by dividing the CCS into the annual production to estimate the cost per tonne of product.

In ammonia and urea production the CCS cost is fully allocated to urea production since all ammonia is converted into urea. The CCS cost is divided into the annual production to estimate the cost per tonne of product. However, the CCS should be allocated based on identifying in which part of the process (e.g., syngas production, ammonia synthesis, or urea production) within the integrated facilities the $CO_2$ capture is done. The cost should be allocated to the outcome of that part of the process. For instance, the $CO_2$ is captured in the syngas production used in the synthesis of ammonia. Therefore, the CCS cost should be allocated into ammonia production, and in turn, to the urea production based on the amount of ammonia converted into urea.

In this research, a mass-based allocation and energy-based allocation were analyzed in the oil refinery. Those approaches have different outcomes either when a process stream or product stream is used. For instance, allocating the CCS cost using the process stream approach (i.e., either mass-based or energy-based) indicates that 2% of the CCS cost is allocated to propylene production. Unlike the product stream approach that indicates 1%. Additionally, mass-based and energy-based in any of its variations present a similar output regarding the amount of CCS cost that should be allocated to propylene production. Therefore, the propylene production cost should be affected in different magnitude. However, the final product through the value chain should have a small impact on its cost.

The allocation of CCS cost is not limited to primary production. It is also related to the breakdown of the intermediate and final production costs. For instance, the cement production cost with CCS is higher by about 60-90% and the concrete cost by about 8-12%. This can be explained since the cost of cement represents 15% of the total concrete production cost. At the same time, the construction material cost (e.g., steel cost and concrete cost) represents 11% of the total construction cost with a cost impact of 1% higher.

The urea production cost with CCS is higher by about 6% and the corn production cost by about 3%. This can be explained since the cost of urea as fertilizer represents 40% of the total corn production cost.

The propylene production cost with CCS is higher by about 20%, the propylene oxide cost by about 18% since propylene cost represents 90% of the propylene oxide production cost. The polyol cos is higher by about 15% since propylene oxide represents 87% of the total polyol cost. The foam cost is higher by about 9% since polyol represents 58% of the total foam cost. The mattress cost is higher by about 7% since the foam cost represents 80% of the total mattress cost.

It can be concluded that the CCS cost is allocated to the final product based on the cost breakdown of the intermediate and final product through the value chain. The CCS cost is dragged through the value chain to the final product in all the cases. However, the magnitude of this cost would depend on the cost breakdown of each product.The lower the contribution of the primary product cost to the total cost of the intermediate and/or final product, the lower the cost impact in its production cost.

### 5.2.1 LIMITATIONS

As mentioned above, a simplified ammonia/urea production plant did not consider ammonia production used for other downstream products (e.g., ammonium nitrate and nitric acid). Analyzing an industrial complex where ammonia is converted into several products would provide insight into by-products cost allocation from the ammonia production where the $CO_2$ is captured. Also, the production cost (i.e., annualized CAPEX and OPEX) did not consider ammonia cost separately from urea production cost. Analyzing the production cost independently would provide insight into the CCS cost allocation to urea production based on the amount of ammonia converted into urea.

Due to the complexity of the oil refining process, in this research, cost allocation into the process streams in the oil refinery either considering a mass-based or energy-based cost allocation is simplified and limited to the process streams related to the FCC (i.e., where propylene production is done). A complex model with a process simulation and a linear model would provide insight into all oil refined products cost allocation.

Labor cost is excluded in the production of corn. Labor and some variable costs such as electricity are excluded in the production cost of propylene oxide, polyol, foam. Including labor and variable cost would provide insight into an accurate breakdown of the final product cost (i.e., in this case, corn and mattress), and in turn, in the cost impact of the final product.

# 5.3 POLICY IMPLICATIONS

Decarbonization of industrial processes can be achieved by changing to low-carbon fuels, energy efficiency, and consuming electricity from renewable energy. However, process emissions cannot be reduced by the former measures. While CCS is considered a cost-effective mitigation option, a large-scale deployment in the industry required further promotion. Policies are decisive to support and facilitate CCS implementation in industry and support new investments.

There is not a one-size-fits-all policy to support CCS investment in the industrial sector. Policies should consider the challenges that each industry faces as well as its specific characteristics. For instance, most of the industries operate in international markets, instead, cement operates in regional markets.

A carbon price is a key policy instrument either to promote or slow CCS investment. While it is cheaper to pay a carbon price than to invest in CCS, the producers will be reluctant to implement CCS and the large-scale deployment will be unhurried. To address this problem, the $CO_2$ avoided cost should be known to establish a higher carbon price and, therefore, to encourage CCS investment through a carbon price. However, a carbon price requires complementary policy measures such as public procurement, low-carbon product incentives, and feed-in tariffs[12]. A collaboration between the public and private sectors should help to create a market for low-carbon products. For instance, the Netherlands and Canada have implemented public procurement rules to support the use of low-carbon materials for construction projects (IEA, 2019). Incentives for producing low-carbon products should help the producers to cope with the CCS cost allocated to the production cost. Also, the development of shared $CO_2$ transport and storage infrastructure in industrial clusters could help to encourage CCS investment.

The policy instruments mentioned above should be comprehensively implemented to support the dutch industry and producers and encourage the investment in CCS as an option to decarbonize the industry and accomplish the $CO_2$ emissions reduction target. Additionally, these policy instruments should be implemented in the European Union to prevent negative economic impacts and carbon leakage[13].

[12] A policy designed to support the development of renewable energy sources by providing a guaranteed, above-market price for producers (Investopedia, n.d.)

[13] Production is transferred to other countries with laxer emission constraints (European Comission, n.d.).

# 6. CONCLUSIONS

In 2017, industry accounted for about 40% of global energy consumption and one-quarter of direct $CO_2$ emissions (i.e., energy-related and process emissions) being the second-largest source of $CO_2$ emissions (IEA, 2019). To accomplish The Paris Agreement goals, the greenhouse gas emissions produced by human activities are projected to decrease by about 25% by 2030 and net-zero by 2070 (IPCC, 2018).

Carbon capture and storage (CCS) consist of $CO_2$ capture from emissions point sources (e.g., furnaces, flue gas). Then, the $CO_2$ stream is purified and compressed to be for long-term storage (IEA, 2019). CCS provides a solution to reduce $CO_2$ process emissions in the industrial sector that cannot be avoided by switching to low-carbon fuel or electricity use. For instance, $CO_2$ emissions as an inherent product of chemical reactions. However, CCS implementation in the industry can lead to a substantial increment in the cost of industrial plants. According to IEA (2016,p.89): "the solution might lie in a concept of layered incentives, whereby the additional cost of CCS is covered throughout the chain'' within a system made up of three elements; producer of industrial products (e.g., cement producer), an industrial consumer (e.g., construction sector consuming cement), and a final-consumer (e.g., people buying a house).

To this end, the purpose of this study is to assess the product cost impact on final consumers through a value chain. This study was conducted through three case studies to evaluate several industries, value chains, and final products. After the discussion of the results and analysis the main research question is answered:

*To what extent does CCS implementation in primary production translates the cost and the $CO_2$ emission reduction across the industry value chain from industrial production to the final product?*

This study presents that CCS implementation in the cement industry resulted in a higher production cost of about 60-90% while 90% of the direct emissions are avoided. In the steel industry, CCS implementation resulted in a higher production cost of 14% while 47% of the direct emissions are avoided. However, when cement (i.e., used to produced concrete) and steel are used as construction materials to build a bridge, its construction cost resulted in a negligible impact of 1% higher while 60% of the $CO_2$ emissions along the value chain are avoided.

In the fertilizer industry, CCS implementation resulted in a higher urea production cost of 6% while 90% of the direct emission is avoided. However, when urea is used as fertilizer to grow corn, its operating cost resulted in a small impact of 3% higher while 83% of the $CO_2$ emissions along the value chain are avoided.

CCS implementation in the oil refining industry resulted in a higher processing cost of 20% while 64% of the direct emissions are avoided. It is also assumed that the propylene processing cost increases by 20%. However, when propylene (i.e., used to produce propylene oxide, polyol, and in turn foam) is used as material to produce a mattress, its production cost resulted in a small impact of 7% higher.

It can be concluded that CCS implementation in industrial processes resulted in a substantial cost impact while a large amount of $CO_2$ is avoided. It is demonstrated that the cost impact through the value chain decreases until the final product has a minimal o negligible impact on its cost. This goes along with a substantial reduction in the $CO_2$ emissions along the value chain.

In the sensitivity analysis, it was observed that the electricity-intensive capture technologies are sensitive to a variation in the electricity cost having an impact on the production cost, capture cost and $CO_2$ avoided cost or natural cost. On the other hand, the capture technologies that require fossil fuel are sensitive to a variation in the coal and natural gas costs. Besides, the production cost, capture cost, and $CO_2$ avoided cost are less sensitive to a variation of CAPEX of capture technology compared to variations in electricity and natural gas costs.

A carbon price of 45€/$t_{CO2}$ is not sufficient for the production cost with CCS to be lower than the production cost without CCS. Also, the same carbon tax value would have a different impact on the production cost with and without CCS.

Finally, unlike previous studies, this research provides insight into the implementation of CCS in industrial production from a consumer perspective (i.e., the cost impact on the final product). The impact of implementing CCS in two different industries (e.g., cement and steel) to produce a final product is analyzed. Also, this research provides insight into CCS implementation in industries with high consumption products. It can be concluded that implementing CCS in industrial processes offers a solution to decarbonize industrial processes with a small impact on the final product cost.

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# 7. APPENDIX: CASE STUDIES DESCRIPTION

Utilities and consumables prices used in the estimation of primary production costs in 2018 are presented in Table 7.1. The prices are kept constant for a reference case and CCS scenarios.

*Table 7.1 Prices of utilities and consumables*

| | €$_{2018}$ |
|---|---|
| Electricity [a] | 62 (€/MWh) |
| Coal [b] | 3.3 (€/GJ) |
| | 90.75 (€/t) |
| Natural gas [c] | 6.5 (€/GJ |
| Iron Ore [d] | 59.1 (€/t) |

[a] Eurostat. Non-households price in the Netherlands
[b]Indexmundi. Australian thermal coal, 2600 kJ/kg
[c]Eurostat. Price in the Netherlands
[d] Indexmundi. Iron ore 62%Fe

*Table 7.2 Chemical Engineering plant cost index (CEEI,2019)*

| Cost year | CEPCI | Cost year | CEPCI |
|---|---|---|---|
| 2018 | 603.1 | 2013 | 567.3 |
| 2017 | 567.5 | 2012 | 584.6 |
| 2016 | 541.7 | 2011 | 585.7 |
| 2015 | 556.8 | 2010 | 550.8 |
| 2014 | 576.1 | | |

## 7.1 CASE STUDY I: BRIDGE

### 7.1.1 CEMENT PRODUCTION

The reference cement plant is based on the European Cement Research Academy (ECRA) characteristics. The cement plant has a capacity of 1Mt clinker per year (1.36 Mt cement) corresponding to a typical size for European cement plants with 330 days per year run time (Voldsund et al., 2018). The cement production process (without $CO_2$ capture) consists of a dry kiln process with three stages and it is presented in *Figure 7-1*. First, in the raw material preparation, the limestone is preheated in a five-stage cyclone and fed to a precalciner where it decomposes into calcium oxide and $CO_2$. The second stage is the pyro-processing where the product from the precalciner is fed to a rotatory kiln to produce clinker. Cement preparation is the last stage where the clinker is grinded with gypsum to produce cement (IEAGHG, 2013a). A selective non-catalytic reduction (SNCR) system is installed in the kiln as control measure for $NO_x$ emissions. There is fuel consumption (e.g., coal) in the pre-calciner and for the rotatory kiln. Electricity is imported from the grid, and steam is generated from waste heat. (Voldsund et al., 2018).

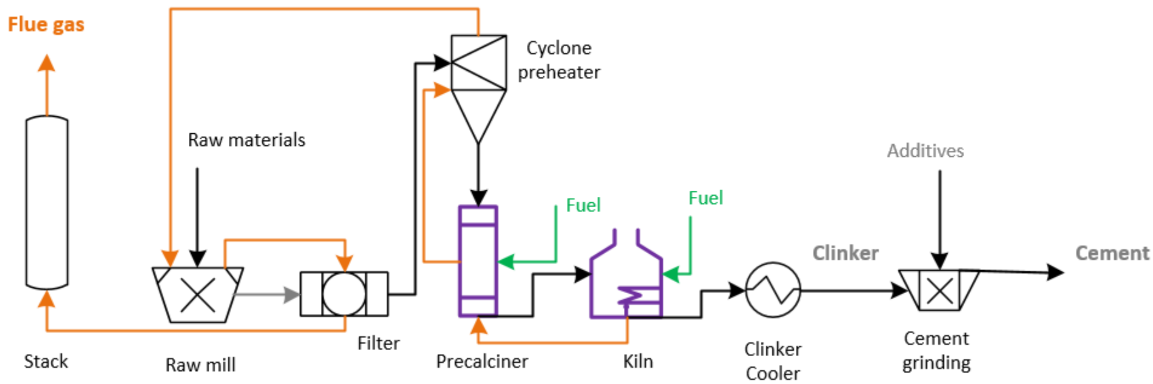


*Figure 7-1 Cement production process in the reference plant.*
*Adapted from (Voldsund et al., 2018)*

During the cement production process (without CCS) the direct $CO_2$ emissions are originated from the precalciner and the rotatory kiln by the combustion of fossil fuels (e.g., energy-related emissions). Also, unavoidable $CO_2$ is generated as a byproduct from the limestone calcination process (e.g., process emissions) (IEAGHG, 2013a). Emissions sources (e.g., precalciner and kiln) are presented in purple in *Figure 7-1*. Flue gas from the precalciner and rotatory kiln is emitted from a single stack. Utilities, consumables, and specific direct $CO_2$ emissions are presented in *Table 7.3* and are assumed to be constant over the year. Economic data of the reference cement plant is presented in *Table 7.4*.

*Table 7.3 Utilities, consumables, and specific CO2 emissions for reference cement plant (Voldsund et al., 2018)*

| | |
|---|---|
| Clinker production | 120.65 t/h |
| Clinker/cement factor | 0.737 |
| Coal | 13.93 t/h |
| Coal LHV | 27150 kJ/kg |
| Electricity | 15.88 MW |
| Specific electric power consumption | 132 kWh/$t_{clk}$ |
| | 97 kWh/$t_{cement}$ |
| Specific $CO_2$ emissions | 850 (kg$CO_2$/$_{tclk}$) |

*Table 7.4 Economic data for reference cement plant (Voldsund et al., 2018)*

| | |
|---|---|
| Cost basis | €$_{2014}$ |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (€/$t_{clk}$) | |
| Raw meal | 5 |
| Coal | 9.4 |
| Electricity | 7.7 |
| Ammonia for SNCR | 0.7 |
| Miscellaneous | 1.1 |
| Fixed OPEX (€/$t_{clk}$) | |
| Operative, administrative and support labor | 8.7 |
| Insurance and local taxes | 4.2 |
| Maintenance cost | 5.3 |
| Total Plant costs (M€) | 203.8 |
| CAPEX (€/$t_{clk}$) | 20.6 |
| Total production cost (€/$t_{clk}$) | 62.7 |
| Total production cost (€/$t_{cement}$) | 46.2 |

#### 7.1.1.1 CAPTURE TECHNOLOGY

The oxyfuel integration into the kiln implies some modifications in the cement kiln. In the capture process, combustion is done with by an air separation unit (ASU), producing a $CO_2$ stream through a $CO_2$ purification unit (CPU) (Voldsund et al., 2018). Oxyfuel process integration in the reference cement plant is presented in *Figure 7-2*. The ASU and CPU require additional power, some of that can be generated from waste heat by an organic Rankine cycle (ORC). Utilities, consumables and $CO_2$ flow rates are presented in *Table 7.5*. The main additions required for the oxyfuel kiln to the production plant are: rotatory kiln burner for oxyfuel combustion, clinker cooler (with cooler gas recirculation), exhaust gas recirculation system, condensers, gas-gas heat exchangers, waste heat recovery system (ORC), ASU and CPU (Voldsund et al., 2018). Economic data of the reference cement plant with oxyfuel integration is presented in *Table 7.6*. Captured rate is assumed as 90%. $CO_2$ is compressed for pipeline transportation (within the CPU) at 110 bar and a temperature not higher than 30 °C (Voldsund et al., 2018).

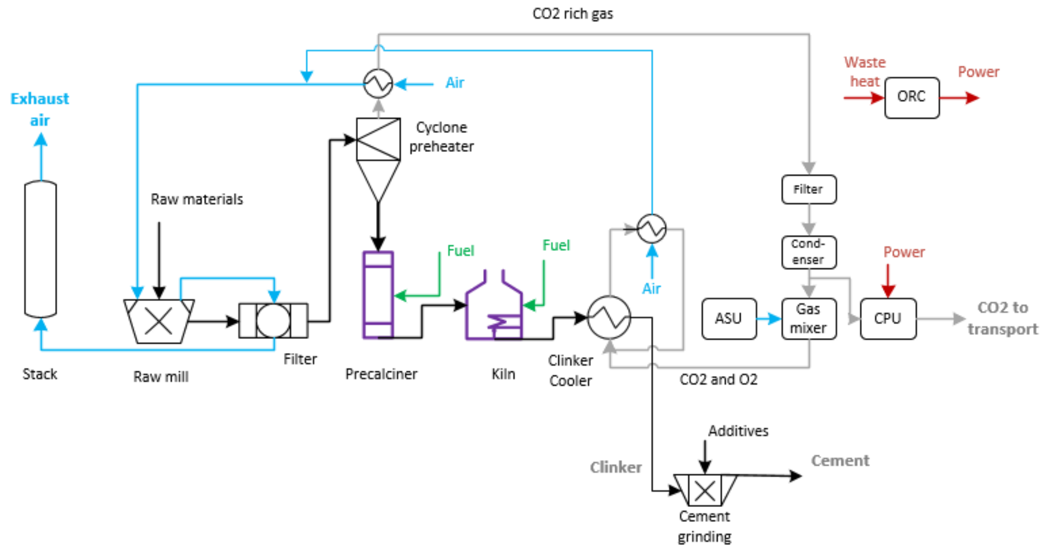


*Figure 7-2 Cement production process in the reference plant with oxyfuel process integration Adapted from (Voldsund et al., 2018).*

*Table 7.5 Utilities, consumables, and specific CO2 emissions for reference cement plant (Voldsund et al., 2018)*

| | |
|---|---|
| Clinker production | 120.65 t/h |
| Clinker / cement factor | 0.737 |
| Coal | 13.93 t/h |
| Coal LHV | 27150 kJ/kg |
| Electricity | 15.88 MW |
| Specific electric power consumption | 132 kWh/$t_{clk}$ |
| | 97 kWh/$t_{cement}$ |
| Specific $CO_2$ emissions | 850 (kg$CO_2$/$_{tclk}$) |

*Table 7.6 Economic data for reference cement plant (Voldsund et al., 2018)*

| | |
|---|---|
| Cost basis | **€$_{2014}$** |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (€/$t_{clk}$) | |
| Raw meal | 5 |
| Coal | 9.4 |
| Electricity | 7.7 |
| Ammonia for SNCR | 0.7 |
| Miscellaneous | 1.1 |
| Fixed OPEX (€/$t_{clk}$) | |
| Operative, administrative and support labor | 8.7 |
| Insurance and local taxes | 4.2 |
| Maintenance cost | 5.3 |
| Total Plant costs (M€) | 203.8 |
| CAPEX (€/$t_{clk}$) | 20.6 |
| Total production cost (€/$t_{clk}$) | 62.7 |
| Total production cost (€/$t_{cement}$) | 46.2 |

The second technology for CO2 capture considered in this study is Calcium Looping (CaL). It is based on the reversible carbonation reaction used to separate $CO_2$ from flue gas. It is applied to a cement plant as a tail-end technology (i.e., not integrated into the kiln as oxyfuel process). The flue gas from cement kiln is sent for purification to the CaL system, CaO rich purge from the CaL system is added to raw material replacing part of the limestone (Voldsund et al., 2018). Calcium-Looping process within the reference cement plant is presented in *Figure 7-3*. The process requires oxygen that is generated by an ASU, a supply of limestone, and coal. ASU, core CaL process, and CPU require power that is generated using waste heat by a steam cycle. Also, CaL calciner requires extra fuel consumption (e.g., coal) (Voldsund et al., 2018). Utilities, consumables, and $CO_2$ flow rates are presented in *Table 7.7*. The main additions to the production plant are two reactors (carbonator and calciner), ASU, and CPU. Economic data of the reference cement plant with CaL is presented in *Table 7.8*. $CO_2$ is compressed for pipeline transportation at 110 bar and a temperature not higher than 30 °C (Voldsund et al., 2018).

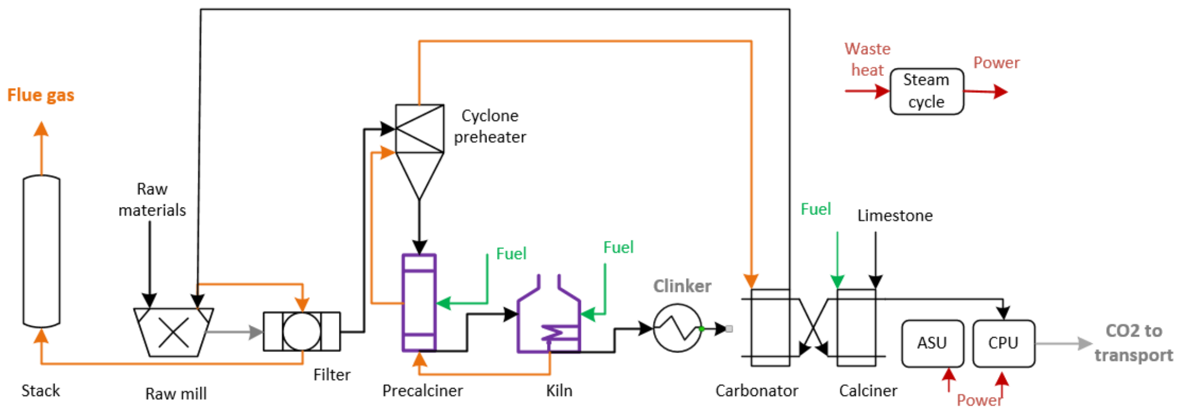


*Figure 7-3 Cement production process in the reference plant with CaL process integration Adapted from (Voldsund et al., 2018).*

*Table 7.7 Cement production process in the reference plant with CaL process integration (Voldsund et al., 2018)*

| | |
|---|---|
| Clinker production | 117.7 t/h |
| Coal | 30.8 t/h |
| Electricity | 6.79 MW |
| $CO_2$ generated fuel combustion | 661.6 ($kgCO_2/t_{clk}$) |
| $CO_2$ generated calcination | 572.9 ($kgCO_2/t_{clk}$) |
| $CO_2$ captured | 1155.5 ($kgCO_2/t_{clk}$) |
| Direct $CO_2$ emissions (after capture) kiln | 48 ($kgCO_2/t_{clk}$) |
| Direct $CO_2$ emissions (after capture) CPU | 31.1 ($kgCO_2/t_{clk}$) |

*Table 7.8 Economic data for reference cement plant with tail-end CaL process (Voldsund et al., 2018)*

| Cost basis | €$_{2014}$ |
|---|---|
| Variable OPEX (€/$t_{clk}$) | |
| Raw meal | 4.9 |
| Coal | 21.3 |
| Electricity | 3.4 |
| Ammonia for SNCR | 0.7 |
| Miscellaneous | 1.1 |
| Fixed OPEX (€/$t_{clk}$) | |
| Operative, administrative and support labor | 11.2 |
| Insurance and local taxes | 8.6 |
| Maintenance cost | 10.8 |
| Total Plant costs, cement kiln + $CO_2$ capture (M€) | 406 |
| CAPEX (€/$t_{clk}$) | 43 |
| $CO_2$ transport and storage cost (€/$t_{CO2}$) | 10 |

## 7.1.2 CONCRETE PRODUCTION

Cement, crush aggregates, sand, water, and admixtures are the raw materials required to produce Ready-Mix Concrete (RMC) (Rootzén & Johnsson, 2017). *Table 7.9* presents the breakdown of those materials, its unit cost, and its consumption per cubic meter ($m^3$) of concrete.

*Table 7.9 Concrete raw materials costs and composition (Rootzén & Johnsson, 2017)*

| Raw material per $m^3$ of concrete | $€_{2010}$/kg | Kg/$m^3$ |
|---|---|---|
| Crush aggregates | 0.02 | 950 |
| Sand | 0.02 | 900 |
| Cement | | 340 |
| Water | 0 | 190 |
| Admixtures | 1.5 | 2 |
| Density (kg/$m^3$ concrete) | | 2382 |

A breakdown of RMC production cost is presented in *Table 7.10*. Raw materials cost is assumed to be equal to 50% of production cost. Plant cost, fixed cost, and delivery costs together are assumed to be equal to the material cost.

*Table 7.10 Breakdown of RMC total production cost (Rootzén & Johnsson, 2017)*

| | |
|---|---|
| **Variable cost** | |
| Raw materials | 50% |
| Delivery cost* | 20% |
| Fixed cost | 25% |
| Plant cost | 5% |

*Including driver wages and fuel cost

## 7.1.3 STEEL PRODUCTION

The reference integrated steel mill plant has a capacity of 4Mt hot rolled coil (HRC) per year corresponding to a typical size for a Western Europe plant (IEAGHG, 2013b). The steel production process (without CO2 capture) consists of blast furnace route (BF-BOF) with five stages and it is presented in *Figure 7-4*. First, the raw material preparation where the coke, lime, and iron ore are produced in the coke oven and the sinter unit, respectively. The second stage is the pig iron making process within the blast furnace. Then, the pig iron is fed to the basic oxygen furnace (BOF) for steelmaking process and impurities removal. The fourth stage is the lab casting. Finally, the steel is reheated and rolled (IEAGHG, 2013b). A natural gas power plant to generate electricity, a boiler to generate steam, and air separation units are included as part of the integrated steel mill (IEAGHG, 2013b).

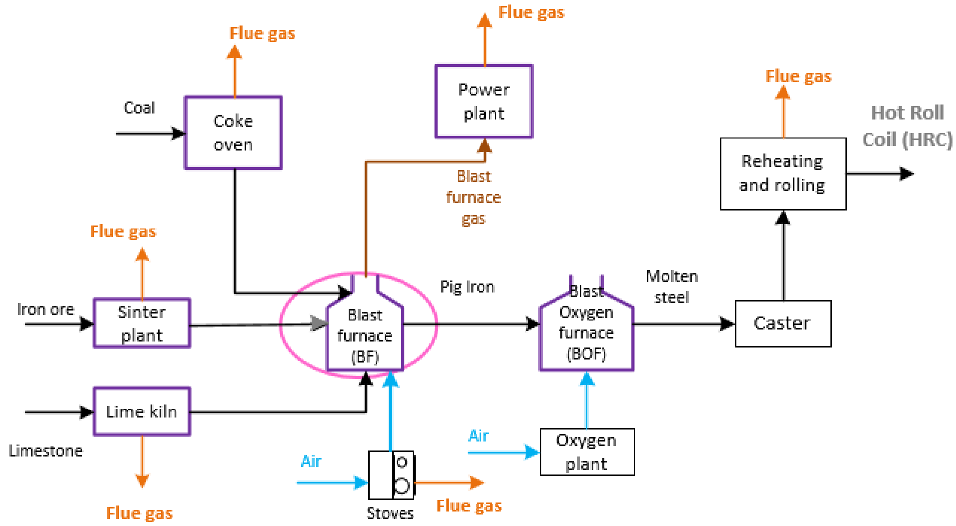


*Figure 7-4 Steel production process in the reference integrated steel mill Adapted from (IEAGHG, 2013b)*

During the steel production process (without CCS) the direct $CO_2$ emissions come from the blast furnace, the power plant, coke ovens, lime kilns, and sinter plant accounting for approx. 90% of the total $CO_2$ emitted in the steel mill (IEAGHG, 2013b). In *Figure 7-4*. emissions sources are illustrated in purple, and possible capture sources are illustrated in pink. Utilities and consumables are presented in *Table 7.11*. and are assumed to be constant over the year. Direct $CO_2$ emissions generated on-site is presented in *Table 7.12* . Economic data of the reference steel mill plant is presented in *Table 7.13*.

*Table 7.11 Utilities and consumables for reference steel mill plant (IEAGHG, 2013b)*

| **Clinker / cement factor** | **0.737** |
|---|---|
| Coking coal | 16.3 (GJ/t $_{HRC}$) |
| | 31.1 (GJ/t$_{coal}$) |
| PCI coal | 5 (GJ/t $_{HRC}$) |
| | 33.4 (GJ/t $_{coal}$) |
| Natural gas | 0.849 (GJ/t $_{HRC}$) |
| Iron ore | 0.88 (t /t $_{HRC}$) |
| Electricity | 400.1 (kWh/ t $_{HRC}$) |

*Table 7.12 Direct CO2 emissions generated in the reference steel mill plant (IEAGHG, 2013b)*

| Source | $KgCO_2/\ t_{HRC}$ |
|---|---|
| Coke oven flue gas | 191.37 |
| Coke oven flare gas | 3.3 |
| Sinter plant flue gas | 289.46 |
| Hot stoves flue gas | 415.19 |
| Blast furnace flare | 19.73 |
| Blast oxygen furnace | 51.02 |
| Continuous casting | 0.8 |
| Reheating furnace flue gas | 57.71 |
| Hot rolling mills | 0.04 |
| Lime plant flue gas | 71.62 |
| Power plant flue gas | 982.13 |

*Table 7.13 Economic data for reference steel mill plant (IEAGHG, 2013b)*

| **Cost basis** | **$US\$_{2010}$** |
|---|---|
| Conversion rate € 1 = US$1.34 | |
| Operational life | 25 y |
| Discount rate | 10% |
| Variable OPEX ($\$/t_{HRC}$) | |
| Fuel & reductant (coking coal, PCI coal and natural gas) | 118 |
| Iron ore | 120 |
| Scrap & ferroalloy | 53 |
| Fluxes | 11 |
| Consumables & others | 12 |
| Fixed OPEX ($\$/t_{HRC}$) | |
| Labor | 70 |
| Maintenance & others | 55 |
| Total Plant costs (M$) | 4,124 |
| CAPEX ($\$/t_{HRC}$) | 135 |

### 7.1.3.1 CAPTURE TECHNOLOGY

The oxy-blast furnace implies the replacement of a hot blast with pure oxygen. $CO_2$ from the top gas is removed to produce OBF process gas (OBF-PG) (IEAGHG, 2013b). The main modifications include changes to the coke and sinter production. Most of the top gas is sent back to OBF reducing its coke consumption, reducing direct $CO_2$ emissions from the coke plant, and increasing the blast furnace productivity. Oxy-blast furnace process within reference steel mill plant is presented in figure_. $CO_2$ from the top gas generated by the OBF is captured using MDEA/Pz solvent. The main additions include a steam generation unit and an ASU to produce oxygen. Economic data of the reference steel mill plant with OBF process is presented in *Table 7.14*. The power plant, steam generation plant, and the OBF-PG heaters require additional natural gas consumption. On-site direct $CO_2$ emissions (after capture) are presented in *Table 7.15*. $CO_2$ is compressed for pipeline transportation at 110 bar.

*Table 7.14 Economic data of the reference steel mill plant with OBF process (IEAGHG, 2013b)*

| | |
|---|---|
| **Variable OPEX ($/t$_{HRC}$)** | |
| Fuel & reductant (coking coal, PCI coal and natural gas) | 139 |
| Iron ore | 121 |
| Scrap & ferroalloy | 54 |
| Fluxes | 10 |
| Consumables & others | 14 |
| Fixed OPEX ($/t$_{HRC}$) | |
| Labor | 71 |
| Maintenance & others | 61 |
| Total Plant costs (M$) | 4,877 |
| CAPEX ($/t$_{HRC}$) | 161 |
| $CO_2$ transport and storage cost (€/t$_{CO2}$) | 10 |

*Table 7.15 Direct CO2 emissions (after capture) of the reference steel mill plant with OBF process (IEAGHG, 2013b)*

| Emission sources | $CO_2$ generated (before capture) | $CO_2$ captured (CCS scenario) | $CO_2$ generated (after capture) |
|---|---|---|---|
| Coke oven flue gas | 191.37 | 66.28 | 125.09 |
| Coke oven flare gas | 3.3 | | |
| Sinter plant flue gas | 289.46 | 23.81 | 265.65 |
| Hot stoves flue gas | 415.19 | | |
| Blast furnace flare | 19.73 | | |
| Blast oxygen furnace | 51.02 | | 51.02 |
| Continuous casting | 0.8 | | 0.8 |
| Reheating furnace flue gas | 57.71 | | 57.71 |
| Hot rolling mills | 0.04 | | 0.04 |
| Lime plant flue gas | 71.62 | | 71.43 |
| Power plant flue gas | 982.13 | 771.03 | 211.1 |
| OBF flue gas | | | 43.05 |
| Steam generation unit | | | 280.12 |
| Total (Kg$_{CO2}$/t$_{HRC}$) | 2082.37 | 861.3 | 1106.01 |
| Total (t$_{CO2}$/t$_{HRC}$) | 2.08 | 0.86 | 1.11 |

### 7.1.3.2 STEEL PRODUCTS

HRC is converted into several products and forms of steel (e.g., wire, rod, and structural steel) utilizing some finishing tasks performed in the steel mill plant. A relative cost[14] is used to represent the differences in each steel product cost (Rootzén & Johnsson, 2016). Moreover, product conversion generates $CO_2$ (i.e., additionally to HRC production emissions). The commercial prices of different steel products, its relative costs, and its specific emissions are presented in Table 7.16.

*Table 7.16 Commercial prices, relative cost, and specific emissions of different steel products*

| Product category | Commercial prices[a] (€$_{2018}$/t) | |
|---|---|---|
| Hot rolled coil | 526 | |
| Wire/rod | 531 | |
| Structural steel (sections and beams) | 653 | |
| **Product category** | **Relative cost[b]** | **$CO_2$ emissions[c] ($t_{CO2}/t_{steel}$)** |
| Hot rolled coil (HRC) | 1 | |
| Wire/rod | 1 | 0.3 |
| Structural steel (sections and beams) | 1.23 | 0.3 |

[a] Excluding delivery cost, (MEPS, 2018)
[b] Relative cost estimated based on commercial average price (MEPS, 2018)
[c] Specific direct $CO_2$ emissions (Rootzén & Johnsson, 2016)

## 7.1.4 TRANSPORT

For cement delivery (i.e., from cement producer gate to concrete producer gate) a distance of 100 km is assumed. For concrete delivery, a maximum distance of 80 km radius is assumed to prevent cold joint (Al-Araidah et al., 2012). Also, the delivery is performed by mixing trucks[15] with a maximum capacity of 9 $m^3$ (Al-Araidah et al., 2012). Steel, unlike cement and concrete markets, is traded globally. Therefore, the same distance as the former markets are not assumed for delivery cost estimation. However, as is proposed Rootzén & Johnsson, 2016 the transport cost of steel is estimated to 5-15% of the selling price of steel products (i.e., considering a profit per tonne of 25 €$_{2010}$). Truck characteristics are presented in

*Table 7.17*. Fuel characteristics are presented in *Table 7.18*. Trip characteristics are presented in *Table 7.19*.

[14] Relative cost (or price) is a cost (price) in terms of another cost (price) (i.e., ratio of two prices).

[15] Due to data availability, mixing truck investment is assumed to be equal to the investment of trailer and tires for a fuel container taken from (Kennedy et al., 2019)

*Table 7.17 Truck characteristics (Kennedy et al., 2019)*

| | |
|---|---|
| Truck characteristics | |
| Truck type | Volvo FH16 cabin |
| Max truck weight (t) | 40 |
| Kerb weight trailer and cabin (t) | 15 |
| Truck investment | |
| Volvo FH16 cabin (€$_{2019}$) | 90,000 |
| Trailer and tires (T-10) (€$_{2019}$) | 25,000 |
| Trailer and tires (fuel container) (€$_{2019}$) | 32,000 |
| Lifetime (y) | 7 |
| Operational cost (% of investment) | |
| Maintenance and repair | 6 |
| Tires | 3 |
| Insurance | 4 |

*Table 7.18 Fuel characteristics (Kennedy et al., 2019)*

| | |
|---|---|
| Fuel characteristics | |
| Fuel consumption (L/km) [a] | 0.3 |
| Calorific value (MJ/L) [b] | 37.7-39.1 |
| Fuel emission factor (kg $CO_2$/GJ) [c] | 72.5 |
| Fuel price (€$_{2018}$/L) | 1.3 |

[a](Kennedy et al., 2019)
[b] (Speight, 2011)
[c](P.J. Zijlema, 2019)

*Table 7.19 Trip characteristics*

| | |
|---|---|
| Trip characteristics | |
| Average speed (km/h) | 60 |
| Full time equivalent (FTE) (h/y) | 2080 |
| Salary (€$_{2019}$/y) | 37,000 |

### 7.1.5 LAKE PONTCHARTRAIN CAUSEWAY

The Lake Pontchartrain Causeway is located in Louisiana, United States representing the longest beam bridge with concrete and steel as construction materials. The amount of those materials is presented in *Table 7.20*.

*Table 7.20 Construction materials of Lake Pontchartrain Causeway (Historic American Record Engineering, 2009)*

| Materials | Units | Quantity |
| --- | --- | --- |
| Concrete | $m^3$ | 224,960 |
| Steel | tons | 24,209 |
| Steel rods | | 21,509 |
| Structural steel | | 2,700 |

The cost estimation model for the PSC beam bridge by Kim et al., 2009 categorized the bridge structure into four elements; superstructure, substructure, services and ancillaries, and site preparation. Superstructure costs include the material cost (e.g., steel and concrete), cost of manufacturing PSC beam (i.e., manufacturing of preassembled parts made by concrete), rebar placing cost (i.e., reinforcing concrete with steel), supporting post cost, concrete placing cost, deck finishing (i.e., made by concrete), among others. Substructure costs include piers, foundations, construction joints, and waterproofing costs. Site preparation costs include excavation, compaction, site clearance, among others. Service and ancillaries costs include mechanical and electrical installations, drainage, maintenance facilities, among others. The breakdown of the cost estimation model is presented in *Table 7.21*. The breakdown of the superstructure costs is presented in *Table 7.22*.

*Table 7.21 Breakdown of PSC total construction cost. (Kim et al., 2009)*

| | |
| --- | --- |
| Superstructure | 43% |
| Services & ancillaries | 11% |
| Site preparation | 5% |
| Substructure work | 41% |

*Table 7.22 Breakdown of superstructure elements cost (Kim et al., 2009)*

| | |
|---|---|
| Cost of material | 24% |
| Manufacturing beam | 50% |
| Rebar fabrication/placing | 9% |
| Supporting post | 6% |
| Form work | 5% |
| Slab waterproofing | 3% |
| Concrete placing | 2% |
| Deck finishing | 0.2% |
| Miscellaneous | 1% |

# 7.2 CASE STUDY II: CORN

In this section, the ammonia and urea industries are described. Also, the material and the farming cost breakdowns of corn are described.

## 7.2.1 AMMONIA PRODUCTION

The reference plant has a capacity of 449.5 kt ammonia per year corresponding to a typical size in Europe (IEAGHG, 2017a). The ammonia production (without $CO_2$ capture) is done through the Haber-Bosch process in which ammonia is synthesized from hydrogen (i.e., from natural gas) and nitrogen (i.e., from the air), and it is presented in *Figure 7-5*. The ammonia process is categorized in hydrogen (i.e., syngas) production and ammonia synthesis. First, sulfur compounds are removed from the natural gas feedstock. The second step is the reforming performed in the primary and secondary reformers. In the primary reformer, the desulphurized natural gas is mixed with steam (i.e., based on the steam methane reforming SMR) producing the syngas (i.e., consist of $H_2$, $CO_2$, $CO_2$, $CH_4$, and steam). The syngas and air enter the secondary reformer to provide nitrogen. The third step is the shift section where the CO in the syngas is converted to $CO_2$ and hydrogen. The fourth step is $CO_2$ removal from the syngas by the absorption process (e.g., MDEA solvent). The removed $CO_2$ is used as feedstock in the downstream urea plant (see section 3.2.2). Then, in the methanation section, any CO and $CO_2$ residual in the syngas is removed. Finally, the syngas enters a converter where the ammonia synthesis takes place. About 95% of the ammonia ($NH_3$) produced is converted into urea (IEAGHG, 2017a). Electricity is imported from the grid. Natural gas is used as fuel for the primary reformer burners. Equipment required for steam generation and boiler feed water is included in the ammonia synthesis and syngas generation units (IEAGHG, 2017a).

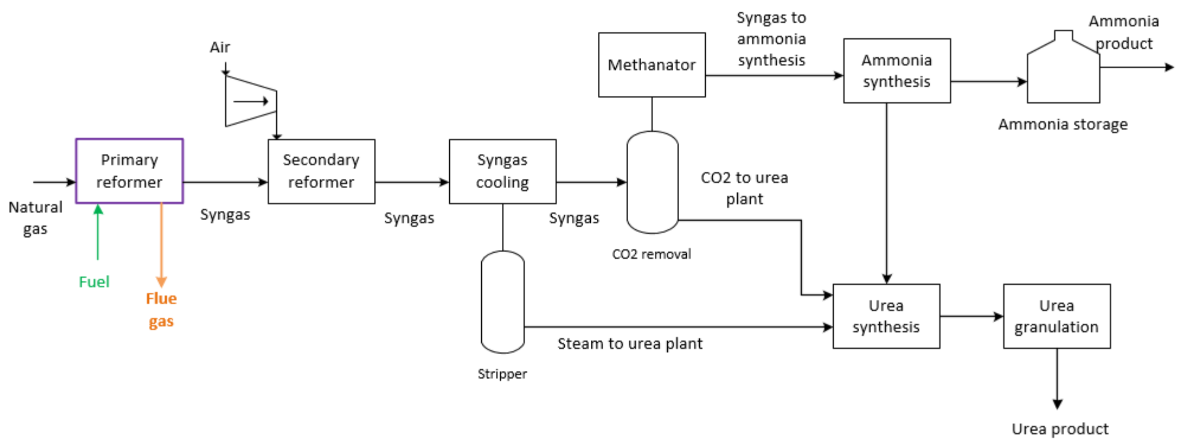


*Figure 7-5 Ammonia and urea production process in the reference plant without CCS Adapted from (IEAGHG, 2017a)*

During the ammonia production process (without CCS) the direct $CO_2$ emissions are generated from the natural gas combustion in the primary reformer and from the reforming section. Emissions sources are presented in purple in *Figure 7-5*.

## 7.2.2 UREA PRODUCTION

The reference plant has a capacity of 752.6 kt urea per year corresponding to a typical size in Europe (IEAGHG, 2017a). Urea production is integrated into the ammonia production facilities (see section 3.2.1). Urea production process (without $CO_2$ capture) is presented in *Figure 7-5*. Ammonia and the removed $CO_2$ from the syngas (i.e., as part of the ammonia process and not related to CCS) react in a synthesis reactor to form urea. Then, urea enters to the granulation unit. The granulation unit is installed in the urea production facilities (IEAGHG, 2017a).Electricity is imported from the grid. Equipment required for steam generation and boiler feed water are included in the ammonia synthesis and syngas generation units (IEAGHG, 2017a).

Utilities, consumables, and specific direct $CO_2$ emissions for the integrated ammonia/urea production are presented in *Table 7.23* and are assumed to be constant over the year. Economic data of the integrated plant is presented in *Table 7.24*. It is worth mentioning that since ammonia and urea production are integrated in the same facilities, data is reported per tonne of urea.

*Table 7.23 Utilities, consumables, and specific CO2 emissions for the integrated ammonia/urea reference plant (IEAGHG, 2017a)*

| | |
|---|---|
| Ammonia production | 1350 t/d |
| | 449.5 kt/y |
| Ammonia converted to urea | 95% |
| Ammonia product to BL | 68.4 t/d |
| Urea production | 2260 t/d |
| | 752.6 kt/y |
| Natural gas feedstock | 27.021 t/h |
| | 13.343 $GJ/t_{urea}$ |
| Natural gas fuel | 10.630 t/h |
| | 4.984 $GJ/t_{urea}$ |
| Ammonia consumption | 0.57 $t_{NH3}/t_{urea}$ |
| $CO_2$ consumption | 0.73 $t_{CO2}/t_{urea}$ |
| Specific electricity consumption | 0.09 MWh/ $t_{urea}$ |
| Specific $CO_2$ emissions | 0.325 $tCO_2$/ $t_{urea}$ |

*Table 7.24 Economic data for reference the integrated ammonia/urea reference plant (IEAGHG, 2017a)*

| | |
|---|---|
| Cost basis | $€_{2014}$ |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (€/y) | |
| Feedstock & fuel | 82,821,922 |
| Make-up water | 34,847 |
| Electricity (from the grid) | 5,607,120 |
| Chemicals | 200,000 |
| Catalysts | 1,000,000 |
| Fixed OPEX (€/y) | |
| Direct labor | 3,960,000 |
| Adm./gen. overheads | 2,368,656 |
| Insurance & local taxes | 6,559,200 |
| Maintenance | 9,838,800 |
| Total Capital Requirement (M€) | 849.2 |
| Total production cost (€/$t_{urea}$) | 257.3 |

### 7.2.2.1 CAPTURE TECHNOLOGY

The absorption process using MEA solvent is used to capture the $CO_2$ emissions of the flue gas from the primary reformer. The capture unit integration within the reference integrated ammonia/urea plant is presented in *Figure 7-6*. Utilities, consumables and $CO_2$ flow rates are presented in *Table 7.25*. Part of the $CO_2$ captured is used to increase the urea production to 792.5 kt/y meaning that all ammonia is converted into urea (IEAGHG, 2017a). Additional steam is required for the capture unit., therefore some compressors are modified into electrical driven compressors increasing the electricity demand of the plant. The main additions are a $CO_2$ absorption section, heat exchanger network and the $CO_2$ stripper section. Economic data of the reference integrated ammonia/urea plant with CCS is presented in *Table 7.26*. $CO_2$ is compressed for pipeline transportation at 110 bar (IEAGHG, 2017a). Since there is additional $CO_2$ that is captured from the primary reformer flue gas the ammonia production is maximized to 792.5 kt/y, therefore all ammonia is converted into urea (IEAGHG, 2017a).

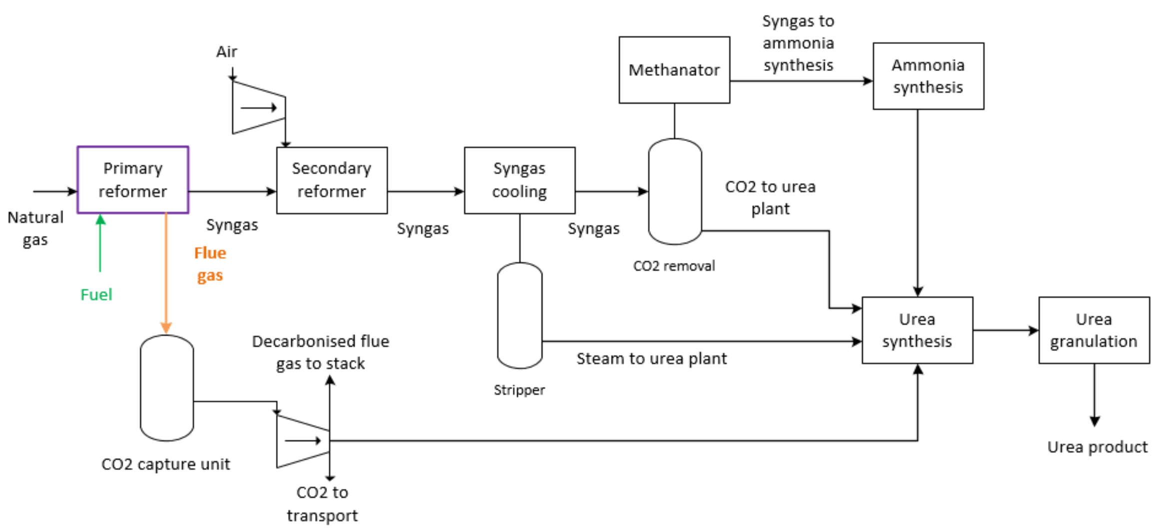


*Figure 7-6 Ammonia and urea production process in the reference plant with CCS Adapted from (IEAGHG, 2017a)*

*Table 7.25 Utilities, consumables, and specific CO2 emissions for reference integrated ammonia/urea plant with CCS (IEAGHG, 2017a)*

| | |
|---|---|
| Ammonia production | 1350 t/d |
| | 449.5 kt/y |
| Ammonia converted to urea | 100% |
| Ammonia product to BL | N/A |
| Urea production | 2380 t/d |
| | 792.54 kt/y |
| Natural gas feedstock | 27.021 t/h |
| | 13.343 GJ/$t_{urea}$ |
| Natural gas fuel | 10.630 t/h |
| | 4.984 GJ/$t_{urea}$ |
| Specific electricity consumption | 0.174 MWh/ $t_{urea}$ |
| Specific $CO_2$ captured | 0.2387 $tCO_2$/ $t_{urea}$ |
| Specific $CO_2$ emissions | 0.0328 |

*Table 7.26 Economic data for reference the integrated ammonia/urea reference plant with CCS (IEAGHG, 2017a)*

| | |
|---|---|
| Cost basis | €$_{2014}$ |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (€/y) | |
| Feedstock & fuel | 82,821,922 |
| Make-up water | 6,465 |
| Electricity (from the grid) | 11,021,840 |
| Chemicals | 200,000 |
| Catalysts | 1,000,000 |
| Fixed OPEX (€/y) | |
| Direct labor | 4,260,000 |
| Adm./gen. overheads | 2,604,024 |
| Insurance & local taxes | 7,366,800 |
| Maintenance | 11,050,200 |
| Total Capital Requirement (M€) | 954.4 |
| Total production cost (€/$t_{urea}$) | 280.3 |

### 7.2.3 CORN

Operating costs in a corn crop are given by the seed, fertilizer, chemicals, electricity, fuel and water costs. *Table 7.27* presents the breakdown of the agricultural costs per acre. Labor is excluded from the operating costs. A food price index of 100.6 for 2018 and 115.8 for 2014 are used.

*Table 7.27 Agricultural costs per acre of corn (FAO, 2016)*

| Operating cost | $USD_{2014}$ | |
|---|---|---|
| Seed | 101.04 | 28% |
| Fertilizer | 149.23 | 42% |
| Chemicals | 29.2 | 8% |
| Custom operations | 18.24 | 5% |
| Fuel, electricity | 32.8 | 9% |
| Irrigation water | 26.17 | 7% |
| Total | 357 | |

## 7.3 CASE STUDY III: MATTRESS

In this section the propylene production from an oil refinery is described. Also, the material cost for polyol, foam, and mattress are described.

### 7.3.1 PROPYLENE PRODUCTION

The reference oil refinery has a capacity of 350,000 barrels per day corresponding to a typical size in Europe(IEAGHG, 2017c). Oil refining and propylene production process (without CCS) are presented in *Figure 7-7*. The crude oil enters to the crude distillation unit (CDU) followed by the vacuum distillation unit (VCD) and then to the fluid catalytic cracking (FCC) where the propylene is produced (IEAGHG, 2017c). Electricity and steam are generated on-site by a natural gas power plant. The annual production of the different oil refined products and its lower heating values are presented in *Table 7.28*.

*Table 7.28 Annual production of the oil refined products and its LHV values (IEAGHG, 2017c)*

| | kt/y | LHV (MJ/kg) |
|---|---|---|
| Road Diesel | 6453 | 42.6 |
| Gasoline U95 Europe | 2988 | 43.4 |
| Jet fuel | 2100 | 43 |
| Heating Oil | 1291 | 42.8 |
| Gasoline U92 USA Export | 1281 | 43.4 |
| Marine Diesel | 860 | 42.8 |
| LPG | 837 | 45.5 |
| Coke Fuel Grade | 825 | 29.5 |
| Propylene | 197 | 45.9 |
| Sulphur | 160 | 9.2 |
| Petrochemical Naphtha | 157 | 44.9 |
| Natural gas consumption (GJ/y) | 9,047,879 | |

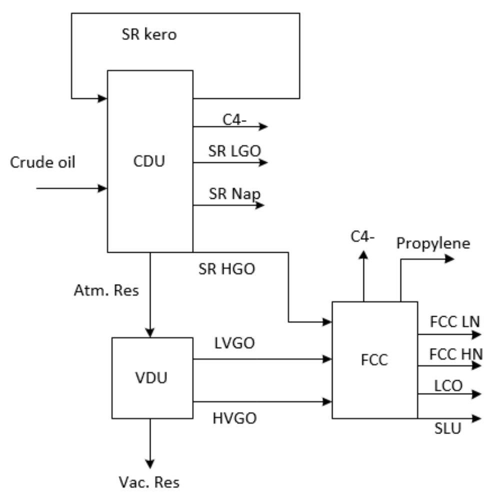


*Figure 7-7 Simplified model of propylene production within in the oil refinery. Adapted from (IEAGHG, 2017c)*

During the oil refining process (without CCS) the largest emission source are the power plant, the crude distillation unit (CDU), the vacuum distillation unit (VCD the fluid catalytic cracking (FCC), and the stem methane reforming unit (SMR) (IEAGHG, 2017c). The emissions from the FCC are generated by burning coke in the cracking process and regeneration of the deactivated catalyst. The emissions from the CDU and VDU are consequence of fuel oil combustion. The power plant emissions come from burning natural gas IEAGHG, 2017c). Utilities and consumables are presented in table_. and are assumed to be constant over the year. Direct $CO_2$ emissions generated on-site are presented in *Table 7.29*. Economic data of the reference plant is presented in *Table 7.30*.

*Table 7.29 Direct CO2 emission in the oil refinery plant without CCS (IEAGHG, 2017c)*

| Unit | kt/y |
|---|---|
| POW | 819 |
| FCC | 446 |
| CDU/VDU A | 413 |
| CDU/VDU B | 413 |
| SMR | 415 |
| NHT/NSU A | 25 |
| NHT/NSU B | 25 |
| CRF A | 153 |
| CRF B | 153 |
| KHT A | 5 |
| KHT B | 5 |
| HDS A | 38 |
| CRF B | 38 |
| KHT A | 45 |
| KHT B | 142 |
| HDS A | 77 |
| HDS B | 137 |
| VHT | 1 |
| HCK | 819 |
| SDA | 446 |
| DCU | 413 |
| SRU | 413 |
| Total | 3351 |

*Table 7.30 Economic data for the oil refining in the reference plant (IEAGHG, 2017c)*

| | |
|---|---|
| Cost basis | $\$_{2015}$ |
| Conversion rate | 1€=1.1$ |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (k€/y) | |
| Natural gas (GJ/y) | 9,047,879 |
| Chemicals and catalyst | 240,900 |
| Raw water | 2,436 |
| Fixed OPEX (k€/y) | |
| Direct labor | 54,320 |
| Maintenance | 54,320 |
| Other | 36,053 |
| Total Capital Requirement (k€) | 9078,096 |

### 7.3.1.1 CAPTURE TECHNOLOGY

The absorption process using MEA solvent is used to capture the $CO_2$ emissions of the flue gas from the CDU, VDU, FCC, SMR, and power plant. The main additions to the oil refinery plant are a desulphuration unit, absorber section, regeneration section, $CO_2$ compression, and an extra power plant. The $CO_2$ emission from the extra power plant is not captured (IEAGHG, 2017c). Utilities, consumables, and $CO_2$ flow rates are presented in *Table 7.31*. Economic data of the reference oil refining plant with CCS is presented in *Table 7.32*. $CO_2$ is compressed for pipeline transportation at 110 bar (IEAGHG, 2017c).

*Table 7.31 Direct CO2 emissions (after capture) of the reference oil refining plant with CCS (IEAGHG, 2017c)*

| | Kt/y |
|---|---|
| $CO_2$ generated (before capture) | 3351 |
| $CO_2$ captured | 2,770 |
| $CO_2$ extra power plant | 638 |
| $CO_2$ generated (after capture) | 1,220 |

*Table 7.32 Economic data for the CCS in the oil refining reference plant (IEAGHG, 2017c)*

| | |
|---|---|
| Cost basis | $\$_{2015}$ |
| Conversion rate | 1€=1.1$ |
| Operational life | 25 y |
| Discount rate | 8% |
| Variable OPEX (k€/y) | |
| Natural gas (GJ/y) | 16,409,242 |
| Chemicals and catalyst | 12,069 |
| Raw water | 930 |
| Waste disposal | 3,326 |
| Fixed OPEX (k€/y) | |
| Direct labor | 2,400 |
| Maintenance | 37,047 |
| Other | 5,855 |
| Total Capital Requirement (k€) | 1,472,903 |

#### 7.3.1.1.1 CCS COST ALLOCATION

To allocate CCS cost using mass-based and energy-based approaches with process stream, the oil refining process is simplified and limited to the outlet streams from other units that are considered inlet streams for the FCC unit. For instance, the streams that are recirculated to the CDU unit and the streams that go directly to other units non-related to FCC are excluded. The simplified model is resented in *Figure 7-7*. The flow rates and LHV for all streams are presented in *Table 7.33*.

*Table 7.33 Flow rates and LHV values (IEAGHG, 2017c)*

| Stream | Flow rate (kt/y) | LHV (MJ/kg) |
|---|---|---|
| | CDU | |
| Crude oil | 16746 | |
| C4- [b] | 243 | 45.30 |
| SR Nap [b] | 2695 | 44.90 |
| SR Kero [b] | 2817 | 43 |
| SR LGO[a] | 3726 | 40.60 |
| SR HGO | 659 | 39 |
| Atm. res. | 6606 | 35.90 |
| | VDU | |
| LVGO | 1108 | 40.60 |
| HVGO | 2311 | 39 |
| Vac. Res. [b] | 3186 | 35.90 |
| | FCC | |
| C4- | 490 | 45.90 |
| Propylene | 197 | 45.90 |
| FCC LN | 901 | 44.90 |
| FCC HN | 451 | 44.90 |
| LCO | 611 | 40.60 |
| SLU | 291 | 39 |

[a] Recirculated to CDU
[b] Excluded, does not affect FCC

## 7.3.2 PROPYLENE OXIDE

The materials cost to produce propylene oxide (PO) is given by the propylene cost and hydrogen peroxide costs. Table 7.34 presents the breakdown of those materials, its unit cost and its consumption per kg of propylene oxide.

*Table 7.34 Propylene oxide raw materials costs and composition*

| Raw material per kg of polyol | $€_{2018}$/kg | $Kg/kg_{PO}$ |
|---|---|---|
| Propylene | 0.85 [a] | 0.77 [c] |
| Hydrogen peroxide | 0.13 [b] | 0.69 [c] |

[a] (ICIS, 2019)
[b](Solvay, 2018)
[c](Industrial Solutions, 2018)

### 7.3.3 POLYOL

The materials cost to produce polyol is given by the propylene, glycol, and monopropylene glycol (MG) costs. *Table 7.35* presents the breakdown of those materials, its unit cost, and its consumption per kg of polyol.

*Table 7.35 Polyol raw materials costs and composition (Fernández-Dacosta et al., 2017)*

| **Raw material per kg of polyol** | **$€_{2015}$/kg** | **$Kg/kg_{polyol}$** |
|---|---|---|
| Propylene | 1.4 | 0.97 |
| Glycol | 1.55 | 0.02 |
| MG | 0.73 | 0.1 |

### 7.3.4 FOAM

The materials cost to produce foam is given by polyol, water, amine, etc. *Table 7.36* presents the breakdown of the materials cost per kg of foam.

*Table 7.36 Breakdown of the materials cost per kg of foam (Usman et al., 2012)*

| **Raw material per kg of foam** | **% of materials cost** |
|---|---|
| Polyol | 58% |
| TDI | 39% |
| Water | 0.4% |
| Amine | 0.1% |
| Stannous | 0.4% |
| Silicone | 2% |

### 7.3.5 MATTRESS

The production cost of a queen mattress is given by the foam cost and quilting cost. Labor is excluded. *Table 7.37*presents the breakdown of the queen mattress production cost.

*Table 7.37 Breakdown of the queen mattress production cost (Brandalyzer, 2019)*

| **Cost element** | **% of materials cost** |
|---|---|
| Foam | 78% |
| Outer fabric | 13% |
| Quilting | 2% |
| Quilting foam cost | 7% |