The Cost to Consumers of Carbon Capture and Storage—A Product Value Chain Analysis

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The Cost to Consumers of Carbon Capture and Storage—A Product Value Chain Analysis

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Abstract: High-cost abatement measures to mitigate greenhouse gas emissions in the basic commodity industry is known to result in substantial increases in the production costs. Consequently, investments in such measures are lagging behind what is required to make deep emission cuts in line with the Paris Agreement. As high-cost abatement measures (such as Carbon Capture and Storage; CCS) are perceived as expensive for the basic commodity producer, this study investigates the impacts down-stream of the product value chain when assuming full cost pass-through (i.e., the cost increase related to basic commodity production is fully passed on down-stream of the product chain to the end-consumer). We investigate the effects on both costs, by means of a techno-economic assessment, and carbon footprints, using a Life Cycle Assessment (LCA), along the product value chain for the case of post-combustion CCS applied to the cement, pulp, Waste-to-Energy (WtE), and refinery industries, towards abating fossil- and process-related emissions and generating negative emissions. Here, we analyse the product value chains that involve cement to a high-speed railway, pulp to a disposable baby diaper, WtE in connection with housing and plastic products, and refineries to different transportation solutions (truck transport and air-freight). The results show that even though the costs for producing basic commodities can increase significantly (200% for cement, 75% for pulp, 230% for heat, and 6–37% for refinery products) when implementing CCS, the increases in prices for end-users are marginal (1% for the railway, 3% for the disposable baby diaper, 1% for the housing, 0.4% for truck transport and 2% for air-freight). Simultaneously, the carbon footprint associated with the end-use may be reduced by up to 36% for the railway, 31% for the diaper, 80% for the housing, and 3–23% for the refinery cases.

Keywords: value chains; CCS; Bio-CCS; costs; emissions reductions; cement; pulp; Waste-to-Energy; refinery

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1. Introduction

Global carbon dioxide (CO_2) emissions need to reach net-zero around mid-century and become net-negative thereafter, in order to comply with the Paris Agreement and restrict global warming to less than 2 °C with reasonable certainty [1]. Negative emissions are needed to compensate for residual greenhouse gas (GHG) emissions in hard-to-abate sectors and to compensate for a likely overshoot in emissions, i.e., net-negative emissions are likely to be required in the second half of the century. Industry accounted for approximately 20% of global GHG emissions in 2019, and is predicted to become one of the sectors with the highest levels of residual emissions [2]. The European Union's emission cap and trade scheme (EU ETS) includes energy-intensive sectors, such as the cement industry, pulp and paper industry, and oil refineries [3]. However, most industries currently receive substantial amounts of free allocation of emission allowances, which means that currently they do not pay for all their emissions according to the Polluter Pays Principle. Within the fourth trading period (Year 2021–2030) of the EU ETS, the total number of yearly emission allowances is decreased, to pursue the objectives of achieving climate neutrality by Year 2050 and reducing net GHG emissions by 55% by Year 2030 relative to the Year 2005 levels [3]. In addition, within the so-called *Fit for 55* initiative, the free allowances will be phased out and replaced by a Carbon Border Adjustment Mechanism (CBAM) and the reduction in yearly allocation of allowances will almost double (yearly reduction of 4.3% compared to 2.2%), with the last emission allowance to be issued in Year 2039. Taken together, it can be expected that allowance prices will increase further from the current (spring of 2023) level of 80–100 €/tCO_2.

Depending on the type of industry, different emission mitigation options exist. Many of the options for achieving deep cuts in emissions are costly and require substantial alterations to the processes, which means that several industries are characterised as 'hard-to-abate'. Applying such measures results in increased production costs, i.e., corresponding to that the cost of the carbon emissions is internalised (see, for example [4–6]). The resulting increase in the product selling price can expose industries to increased competition from regions with less-stringent climate policies. However, even though high-cost abatement measures will result in large production cost increases due to increased operational expenditures (OPEX) and annualised capital expenditures (CAPEX), previous studies have shown that the end-consumer may experience only a marginal cost increase. This principle has been shown assuming full cost pass-through for production cost increases, such as an increased carbon tax [7] and for the implementation of high-cost abatement measures, such as Carbon Capture and Storage (CCS) (see, for example, [8–11]), as is the focus of this work. The costs for implementing CCS in industrial plants differ significantly depending on factors such as emission volumes and CO_2 concentrations in the flue gases, availability of excess heat to drive part of the capture process, logistical conditions for transport to CO_2 storage sites, and whether CCS is implemented as part of a new-built plant or retrofitted to an existing plant. It is, therefore, important to expand upon previous studies with case studies that represent different product value chains.

Previous studies have focused on the cement, steel, and pulp industries (see, for example, [8–11]), while in this study, the number of industries is extended further to include cement, pulp, Waste-to-Energy (WtE), and oil refineries, covering a wider range of end-use products. These industries are of interest because all of them are included in the EU ETS (the WtE sector is included in EU ETS in Sweden and Denmark [12]). Furthermore, the cement industry is a well-known hard-to-abate sector due to its inherent process emissions. The oil refineries are likewise hard-to-abate, since they use fossil feedstocks and the site emissions represent a small percentage of the total life-cycle emissions from their products, i.e., the fuels. The chemical pulp industry and WtE sector both have the possibility to deliver negative emissions due to their large biogenic emissions. Negative emissions can be generated by applying CCS at existing large point sources of biogenic CO_2 emissions, provided that the biomass feedstock is sourced from a system for which the carbon stock is at least maintained or with a net growth (e.g., a well-developed forest management system). Furthermore, the selected industries are interesting to analyse because they vary significantly with regards to the types of end-uses (i.e., infrastructure/building projects or bulk products) and end-consumers (i.e., governmental or private consumers). The basic commodities are further associated with usage in a variety of down-stream sectors that are in great need of decarbonisation, such as buildings and infrastructure, road transportation and aviation, and housing in cities. Previous studies have focused on either single industries and/or single end-product systems (e.g., [8–11]). The wide range of industries and end-uses explored in the present work, therefore, offers additional comparisons and promotes generalisability across industries.

We investigate the effects on costs, using a techno-economic assessment, and carbon footprints, using Life Cycle Assessment (LCA), along the product value chain from basic product to end-use of post-combustion CCS applied to the above-mentioned industries, with the goals of abating fossil- and process-related emissions and generating negative emissions. The analysis is carried out for several product value chains: cement to a high-speed railway, pulp to a disposable baby diaper, WtE connected to housing through district heating (DH) and municipal solid waste (MSW) handling, and refineries to different transportation solutions. The overall aim of the work is to illustrate the impacts on consumer costs and emissions of applying CCS as a deep mitigation measure.

2. Methodology

The product value chain, which encompasses attaining the feedstock to end-use, is mapped out, and the production cost of the basic commodity is calculated to analyse how the changes in production cost and selling price, including profit margins, affect the cost of the end-use. In this work, full cost pass-through is assumed, meaning that a cost increase in the basic production process is fully passed on down-stream of the product chain to the end-consumer. This is to illustrate how such a cost increase could affect the consumer price. Emission factors for the basic commodity and its end-use are evaluated to analyse how the total life-cycle emissions can be reduced for the basic commodity and end-use product or service when implementing CCS.

The product value chains are analysed through the following three steps:

1. Quantifying the cost increase through the value chain, assuming full cost pass-through;
2. Quantifying the changes in GHG emissions by determining the emissions factors associated with the basic product and its end-use;
3. Identifying actors in the product value chain that play key roles in enabling the implementation of CCS as a mitigation measure.

2.1. Cost Evaluation

This work considers retrofits of existing production facilities with CCS, and the CAPEX of the plant itself is, therefore, assumed to have been depreciated. The basic commodity plants are assumed to be located in Europe and the CCS plant is Nth of a kind. The CAPEX is expressed as the annualised Total Capital Requirement (TCR), which includes direct costs for components, costs for retrofitting the mill, contingency costs, spare parts costs [1% of the Total Plant Cost (TPC)], start-up cost (3% of TPC), owner's cost (7% of TPC), working capital, and interest during the construction phase (8%) [13], as depicted in Figure 1. The owner's cost is covering the costs, for example, for feasibility studies and improving the infrastructure beyond the site boundary, and includes permitting and legal fees. For more detailed information, see [14].

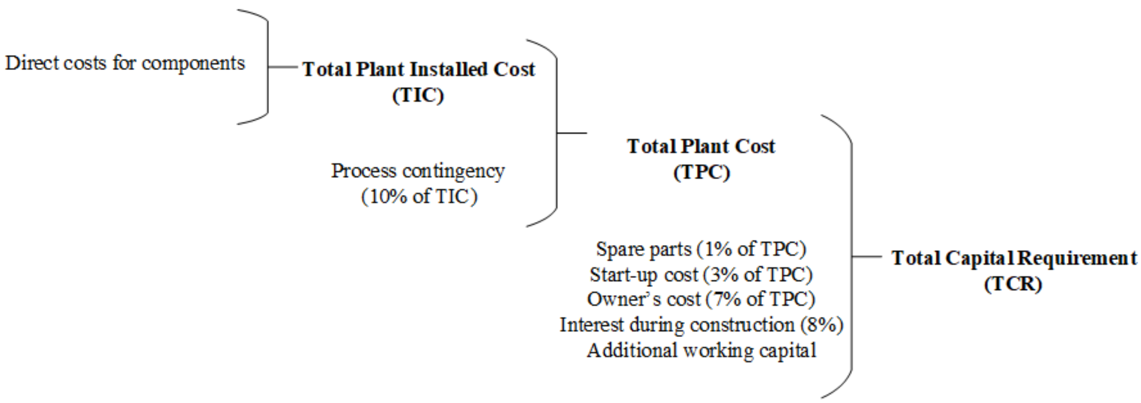

Figure 1. Break-down of total capital requirement cost structure. Adapted from [13].

All costs and prices are adjusted using the Chemical Engineering Plant Cost Index (CEPCI) and expressed in €$_{2020}$. Historically, sectors that are deemed to be at risk of carbon leakage due to international cost competitiveness [15] have received free allocation of emission allowances from the EU ETS cap and trade system. In Phase 4 of the system (2021–2030), these sectors will continue to receive 100% free allocation of emission allowances during the first half of the period [16]. However, the free allocation is planned to be phased out with an increasing rate and be completely phased out by Year 2033 [17].

The CBAM will replace the free allocation as a means to reduce carbon leakage [18]. In this work, a charge on fossil-based emissions of 80 €/tCO_2 is applied to compare the effect of a CO_2 price similar to the EU-ETS allowance price in Year 2022. However, the reference cases do not include any costs for purchasing emission allowances.

The cost of the commodity, $C^{com}_{s,c}$ (€ per functional unit of commodity), with and without CCS for each product p (basic commodity or intermediate product), for each sector s, is evaluated according to Equation (1) [9]:

$$C^{com}_{s,c} = OPEX^{var}_{s,c} + OPEX^{fix}_{s,c} + CAPEX_{s,c} + C^{delivery}_{s,c} + C^{transport} + C^{tax} \quad (1)$$

where $OPEX^{var}_{s,c}$ is the variable operational expenditures, $OPEX^{fix}_{s,c}$ is the fixed operational expenditures, $TCR_{s,p}$ is the annualised investment cost, $C^{delivery}_{s,c}$ is the delivery cost of the industrial product, $C^{transport}$ is the transportation and storage cost of CO_2, and C^{tax} is the carbon tax.

$CAPEX_{s,c}$ is calculated according to Equation (2) [5]:

$$CAPEX_{s,c} = \frac{TCR_s \cdot i}{1-(1+i)^{-L}} \quad (2)$$

where TCR is the Total Capital Requirement, i is the discount rate (assumed to 8%), and L is the economic life-time (assumed to be 25 years). The TCR of the CCS plant is scaled to the production capacities of the plants used in this work, according to Equation (3) [19]):

$$TCR_j = TCR_{ref} \cdot \left(\frac{P_j}{P_{ref}}\right)^n \quad (3)$$

where TCR_j is the TCR of the scaled emission source, TCR_{ref} is the TCR of the reference emissions source, P_j is the production capacity of the emission source to which the cost is scaled, P_{ref} is the production capacity of the reference emissions source, and n is an equipment-specific scaling factor (in this study, set to 0.6) [19].

2.2. Emissions Factor Evaluation

Life-cycle emissions are calculated for each basic commodity, intermediate product, and end-use, with and without CCS. The emissions are calculated using attributional Life Cycle Assessment (LCA), as this study has a more business-oriented perspective than a systemic one. The primary objective of this emissions evaluation is to compare the carbon footprints of commodities produced with and without CCS. Moreover, environmental impacts related to new installations of capital goods, i.e., the CCS facilities and related equipment, are excluded from the LCA because they generally have limited impacts on the Global Warming Potential (GWP).

All the industries studied use biogenic feedstocks to some extent, so the origin and handling of the feedstock are of high importance. Biomass used in production is assumed to be produced from forest management systems that at least maintain the carbon stock in the biomass system, such that the biogenic emissions are assumed to be accounted for as zero emissions in this work. Yet, the biogenic emissions are presented in the results, as they show the potential for creating negative emissions (or any other use of the CO_2, such as for electrofuel production). Moreover, the net changes in carbon stocks and GHG emissions and removals from forestry activities are reported in the land use, land-use change and forestry (LULUCF) sector according to the Kyoto Protocol [20]. When evaluating the emissions factor of any basic commodity using CCS technologies, captured biogenic emissions are primarily intended to compensate for any residual fossil emissions from the process, and are secondarily intended to be used to create negative emissions. In this work, it is assumed that a commodity can be sold as a climate-positive product, e.g., pulp, when combined with CCS (i.e., Bio-CCS in relation to biogenic emissions). This is simply to ensure that the emissions reductions from CCS follow the cost increases, i.e., added value. As previously explained, negative emissions are in this work assumed to be used primarily to reduce the emissions factor of a product to zero. Thereafter, one could argue that additional negative emissions should be sold on a separate market (e.g., the voluntary carbon market), as carbon dioxide removal (CDR) certificates rather than using them to create climate-positive products. The emissions factor for each basic commodity is evaluated according to GWP100 (thereby including all the relevant GHG emissions), as expressed in Equation (4):

$$EF_{commodity} = \frac{\sum_i E_i}{P_j \cdot CF} \quad (4)$$

where $EF_{commodity}$ is the emissions factor for each basic commodity in $CO_{2,eq}$ per F.U. of commodity, E_i is all the production-related emissions, up-stream and direct emissions (including fossil and negative emissions), P_j is the production capacity of the emissions source, and CF is the capacity factor of the basic commodity plant.

The total emissions related to each end-use are then evaluated using the EF values for each basic commodity (calculated as above) or by using emissions factors from the ecoinvent database for other related materials and activities, as in Equation (5):

$$E_{tot} = \sum_i (M_i \cdot EF_i) \quad (5)$$

where E_{tot} is the total GHG emissions associated with the end-use, M_i is the amount/use of each commodity/material in its respective end-use, and EF_i is the emissions factor for each commodity/material (including direct and indirect GHG emissions).

Table 1 shows the functional unit for each basic and intermediate commodity used in this work.

Table 1. Basic industrial commodities and associated functional units.

Industry	Commodity	Functional Unit
Cement	Cement Concrete	t cement m^3 concrete
Pulp	Pulp	ADt pulp
WtE	Heat Waste management	MWh_{heat} t MSW
Refinery	Fuel	GJ_{fuel}

MSW, municipal solid waste; ADt, 'air-dried tonnes'.

2.3. CCS Configuration and CCS Chain

In this work, a conventional, post-combustion, amine-based CO_2 capture process is assumed with a 90% capture rate for the cement plant, pulp mill, WtE plant, and oil refinery. The CCS plant requires heat for regeneration of the solvent, and the amount of heat needed is in this work assumed to be 2.8 GJ/tCO_2 captured [5]. The heat for the CCS unit can be supplied either internally if there is availability of excess heat of a sufficiently high temperature or externally through the installation of an additional power plant. For the cement plant, no excess heat is available, and an additional power plant needs to be installed to generate steam for the regeneration of the absorbent. The power plant is assumed to be a natural gas (NG)-fired combined cycle unit, and the additional emissions are co-captured [5]. For the Kraft pulp mill, CCS is applied to two out of three emission sources, the recovery boiler and the lime kiln, resulting in an overall capture rate for the mill of 77.5% [14,21]. Heat for the regeneration step is supplied internally, thereby less electricity is produced and sold to the grid in the pulp CCS case, although the same amount of crude tall oil is produced. The WtE plant is a Combined Heat and Power (CHP) plant in which one-third of the emissions is considered fossil and two-thirds are biogenic. Part of the heat production will be used for the CCS plant, meaning that less heat will be available to sell to the DH network. However, this can be counteracted in part by recovering heat from the reboiler using a heat pump. Therefore, two CCS cases are considered in this work. The change in energy output of the WtE plant and its effect on the DH network are determined using the spreadsheet model developed by Beiron et al. [22]. For the oil refinery, it is assumed that CCS is applied to all the stacks with sufficiently high CO_2 concentrations in the flue gases, in line with the work of Biermann et al. [23]. Additional NG must be combusted to supply the heat needed to the reboiler.

The economic life-time of the CCS plant is assumed to be 25 years, with a discount rate of 8% [5,6]. Furthermore, a transportation and storage cost for CO_2 in the range of 35–50 €/tCO_2 is listed in the literature [24,25], and an average value of 42.5 €/tCO_2 is used in this work. It is further assumed that the CO_2 is transported by ship at a pressure of 7 bar, which are the conditions commonly cited in the literature [26,27], and at a temperature of -49.1 °C [13]. The assumed cost for conditioning and compressing the CO_2 is taken from Deng et al., 2019 [13]. Naturally, depending on the geographical location of the CCS plant, the transportation distance will differ. In this work, the distance from plant to CO_2 storage location is assumed to be 2000 km. Several modes of transportation might be needed, e.g., truck, rail transport, pipelines, and shipping. However, in this work, it is assumed that the full distance is covered by shipping.

2.4. Product Value Chains

Figure 2 shows the product value chains considered in this work for the four industries. One or several end-uses are analysed for each industry. Different types of end-uses are considered, representing a variety of end-consumers, including government-funded agencies (in this case, the National Transport Administration), companies and private consumers. The end-uses considered for the industries are: (1) cement to high-speed railway; (2) pulp to disposable baby diaper; (3) WtE to housing and plastic products; and (4) refinery to air-freight and truck transportation. The industries studied have different characteristics and systemic functions, where the cement plant is considered a single-output process, the pulp mill and biorefinery are multi-output processes, and the WtE plant is a multi-functional system. In this type of analysis where full cost pass-through is assumed, the additional costs when implementing CCS must be allocated to the services provided by the basic commodity producer, so as to avoid double-charging customers and double-claiming emissions. The method of allocation of costs and emissions for the basic commodity depends on the type of system considered. With a single-output process, all the production costs and emissions related to the process are directly related to the commodity produced. However, with a multi-output process, an allocation problem occurs whereby the costs and emissions need to be divided between the multiple products produced. In this work, allocation on an energy basis is used for the multi-output processes. Moreover, the WtE plant is considered multi-functional, in that three services are provided: the production of heat; production of electricity; and the service of managing waste. Since the services associated with the WtE plant vary greatly in nature, an economic allocation has been applied according to their market values, as specified in Table 2. It should be noted that for some sectors, such as the WtE sector, system expansion and energy substitution are common approaches, since the commodities produced in this sector are using wider systems settings (e.g., electricity and heat) and a change in the WtE sector might result in changes outside of the value chain studied in this work [28]. However, in this work, the reduced heat production in the WtE plant is accounted for in the intermediate production as a smaller heat delivery to the DH network that needs to be compensated by heat delivery from other units. For more detailed information about the product value chains see the Appendix A.

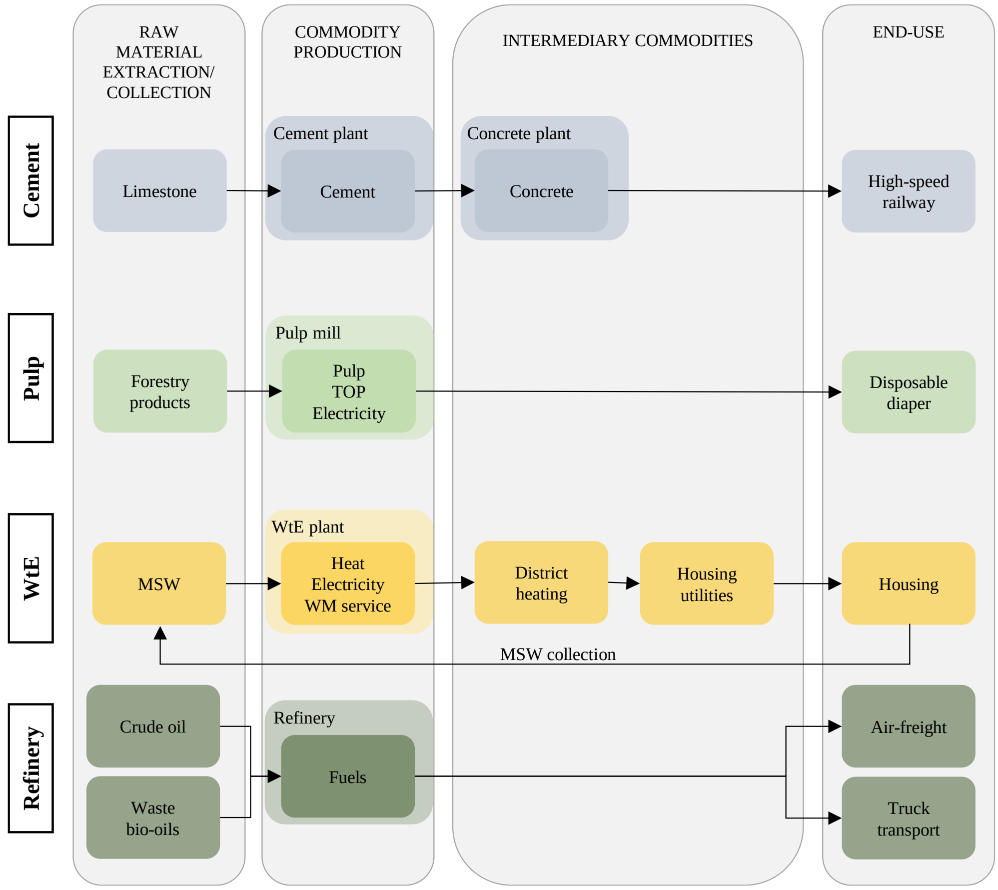

Figure 2. Product value chains analysed in this work: cement to high-speed railway; pulp to disposable baby diaper; WtE to housing and plastic products; and refinery to air-freight and truck transportation.

Table 2. Overview of the economic assumptions made for the cement plant, Kraft pulp mill, WtE plant, and refinery.

General Assumptions	Cement Plant	Kraft Pulp Mill	WtE Plant	Refinery
Installed capacity	1.5 Mt cement	0.8 MADt pulp	0.55 Mt MSW [d]	11.4 Mt crude oil
Average capacity utilisation rate (%)	91.3 [29]	95.9 [29]	97.3 [e]	86.9 [23]
Discount rate (%)	8	8	8	8
Economic life-time (years)	25	25	25	25
Reference plant and CCS configuration	[5]	[14]	[22,30]	[31,32]
Economic Parameters				
Delivery cost	15 €/t of cement [5]	15 €/t of ADt pulp	-	4.1 €/GJ liquid fuel [31]
Average market price per reference unit	64 $€_{2020}$ per tonne of cement [a] [33]	1099 $€_{2021}$ per tonne of air-dried market pulp [c]	49.3 € per tMSW [f] [34] 20.6 € per MWh_{el} [35] 15 € per MWh_{heat} [g] [22]	19.8 €/GJ_{diesel} [i] [36] 13.4 €/$GJ_{jet\ fuel}$ [37]
OPEX				
Electricity price (€/MWh [b])	81.9 € [b]	81.9 € [b]	20.6 € [h] [35]	81.9 € [b]
Natural gas price		-	-	
MEA price (€/t)	1620	1620	1620	1620
Fixed OPEX	[4]	[14]	6% of TCR	[23,38]

[a] European Commission, 2018. Recalculated to $€_{2020}$ values using the cement price index [39]. Thus, the profit margin is 12.4 € per tonne of cement (difference between the selling price and production cost). [b] EU-27 electricity price average in Year 2020 [40]. [c] Average price on the European market per tonne of bleached softwood market pulp [41]. [d] Maximum amount allowed to incinerate according to approved environmental permit. [e] 535 kt MSW incinerated in Year 2021. [f] Average Swedish gate-fee. [g] However, the average DH selling price in the Gothenburg region in 2021 was 826 SEK/MWh, including 25% VAT. [h] Average electricity price in Sweden in Year 2020. [i] Production cost including revenue. The market price is determined by including distribution costs and taxes. The profit margin is assumed to 0.65 € per GJ of product [38].

Table 2 provides an overview of the general economic assumptions and basic commodity plant configurations. The selling price of the basic commodity for the reference case is determined by the market prices for each basic commodity on the European market. The selling price of each commodity for the CCS cases are then determined by the difference in production cost compared to the reference case. Further details of the economic parameters, such as raw material prices, are given in Appendix A Table A1. In the following sections, each product value chain and its associated assumptions are described in further detail.

3. Results

Figure 3 shows the relative cost increases and emissions reductions for the four industries and their related case study end-uses. The production cost of the basic commodity increases significantly for all of the studied industries. However, when moving further down the value chain to the end-use, the cost increment is small for all end-uses. Furthermore, the life-cycle emissions associated with the basic commodity are drastically reduced when implementing CCS, thereby also reducing significantly the emissions related to the end-product. Thus, when the cost of implementing CCS is passed on down the value chain to the end-user, CCS gives a small cost increase for a substantial reduction in the life-cycle emissions of the end-products and services. This is largely because the basic commodity represents a large share of the total emissions but only a small fraction of the total value of the end-product.

The refinery to end-use case studies stand out. The largest share of the life-cycle emissions associated with fuel occur in the use phase, while the emissions related to the production of the fuel are rather limited (5% in this case). Implementing CCS at the oil refinery without changing feedstock will obviously have a limited impact on life-cycle emissions reductions (a reduction of 3% in these cases). To achieve deep cuts in the life-cycle emissions of the fuel, the fossil feedstock used in the refinery must be replaced. The use of waste bio-oils in this work can be seen as a first step towards changing the feedstock, and this can reduce the life-cycle emissions by around 20%, as shown in Figure 3. Yet, changing the feedstock is also more costly due to the high purchase cost of such bio-oils. Therefore, the higher relative increase in costs for the bio and bio-CCS cases reflect the increased purchasing prices of bio-oils compared to crude-oil and not the cost associated with the implementation of CCS. Furthermore, aviation is included in the EU ETS, and for comparison the reference case (conventional fossil jet fuel) has been plotted assuming an added cost of emission allowances of 80 €/tCO_2. At present, the aviation sector acquires the major share (82%) of their allowances for free [42]. Here, we assume that the free allocations have been phased out, i.e., in line with aim of the *Fit for 55* strategy. The 80 €/tCO_2 value is arbitrarily chosen; after Year 2030, when there will be a steep reduction in the free allowances, the allowance price may be higher. The 80 €/tCO_2 level also makes the reference case more expensive than the bio-CCS case. However, it should be noted that if the share of fossil-derived emissions in the use-phase for the bio-CCS case would have to pay 80 €/tCO_2, then this case would still be more expensive than the conventional fuel.

From Figure 3, it can be seen that even though the cost increase linked to implementing CCS is substantial in the basic commodity industry, for most industries it drops rather quickly when considering the impact on the cost of the end-product. This suggests that already an intermediary stakeholder could be an enabler of the transition. For example, in the cement industry, the cost of cement increases by 200%, while the cost of concrete increases by 30%. The concrete producer could, therefore, take up an enabling position. However, it should be noted that even if the cost increment is low for the end-product, it might still be perceived as high by the consumers of intermediary products. For example, even though the cost of housing only increases by 1.2% when implementing CCS in the WtE sector, the price of DH still increases by approximately 9%. Consequently, consumers who consider various heating solutions may find other less-expensive alternatives, such as an individual heat pump in the context of a single-family household. Another issue that is not considered here is the size of the profit margin for the different industries along the value chain. Thus, in the absence of any premium for carbon-neutral or climate-positive products, a large share of the profit margin may be consumed by the implementation of CCS.

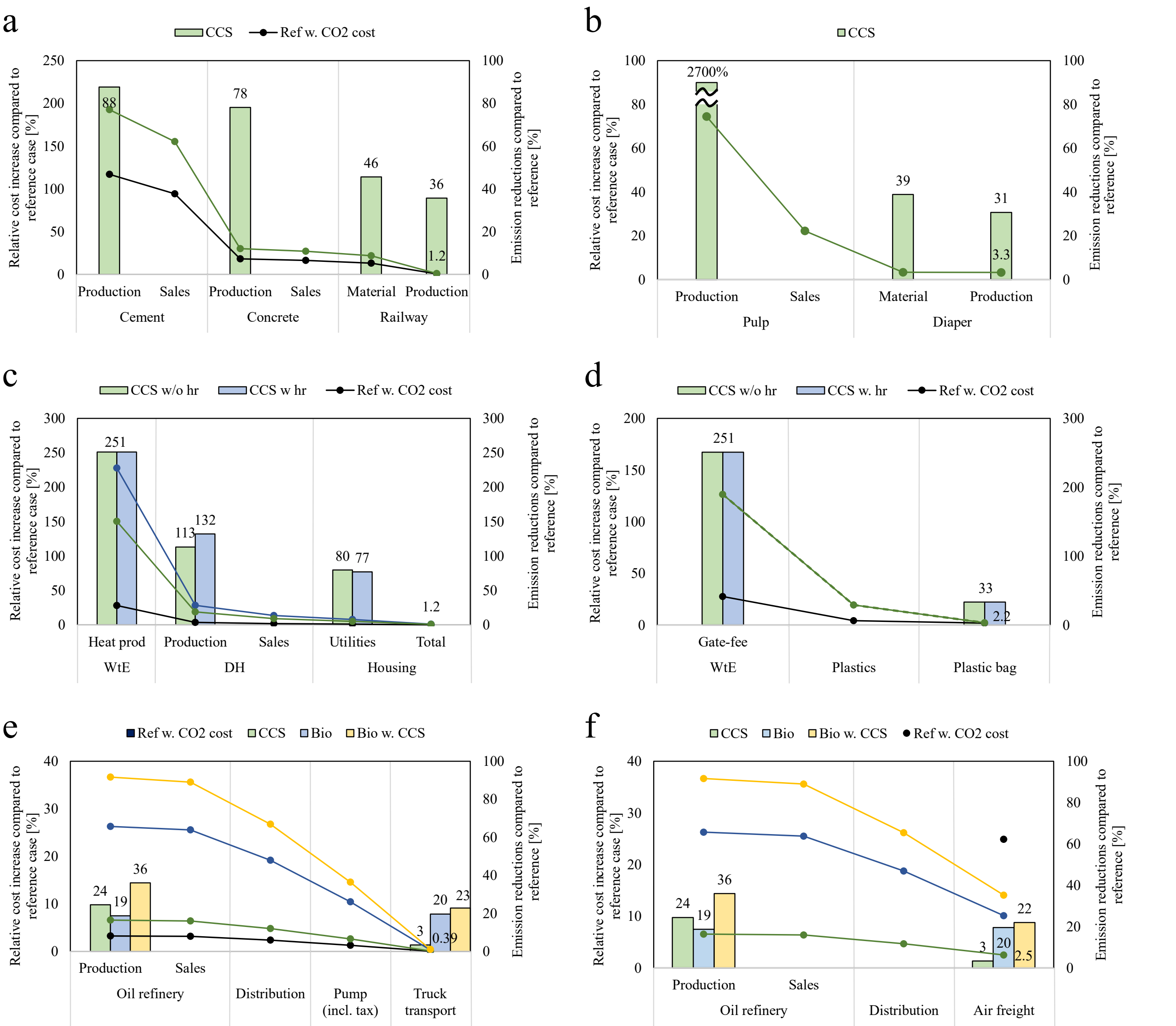

Figure 3. Relative cost increments (line graph) and emissions reductions (bar chart) along the value chain for the end-uses studied. 'Ref w. CO_2 cost' refers to the reference case with an added carbon tax. The emissions reductions are calculated by comparing the emissions factors for CCS-produced commodities with the reference commodity. (**a**) The cement value chain. (**b**) The pulp value chain. (**c**,**d**) The WtE value chain towards housing and plastic bags, respectively, with "hr" meaning heat recovery. (**e**,**f**) The refinery value chains towards truck transport and air-freight, respectively.

Figure 4 shows an overview of the relative cost increases and emissions reductions for the different end-uses explored in this work. As previously stated, most end-uses where the basic commodity represents a significant share of the life-cycle emissions experience a small cost increment, together with a significant reduction in emissions (e.g., railway, diaper, housing, and plastic bag). However, in those cases where the basic commodity represents only a small fraction of the product, such as for the butter package with its content, the emissions reductions associated with that end-use are small. It should also be noted that larger impacts are seen in the air-freight sector compared to the road transportation sector, since aviation fuel is commonly not taxed within the EU and the aviation sector currently receives free allocation of emissions in the EU ETS. In contrast, the fuel used for road transportation is heavily taxed. However, air-freight is a relatively cheap service compared to commercial passenger aviation, meaning that the impact on such an end-product would be smaller.

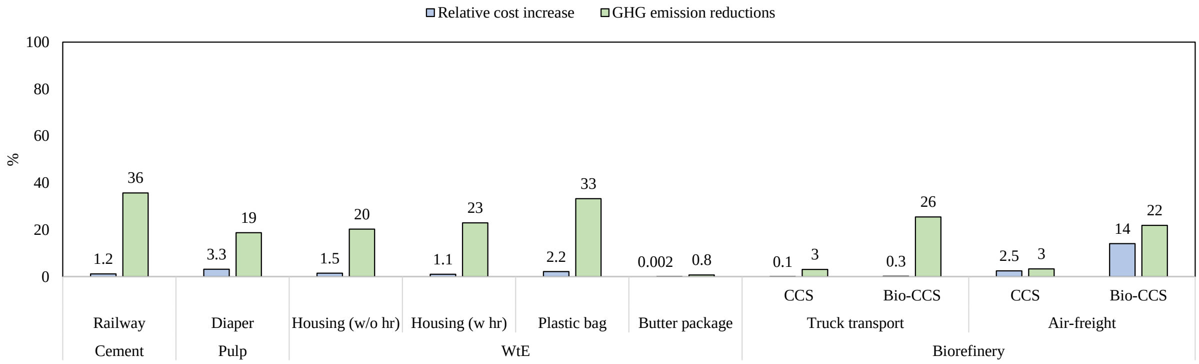

Figure 4. Overview of the relative cost increases and GHG emissions reductions for various end-uses.

3.1. Cost Break-Down

Figure 5 shows the basic commodity production cost break-down per functional unit for the four industries. The implementation of CCS technologies leads to different levels of cost increase, depending on the cost of the reference basic commodity. Notably, industries with inexpensive basic commodities, such as the cement and WtE sectors, experience a relatively significant relative cost increase following CCS implementation (see Figures 3a,c,d and 5a,c,d). In contrast, industries with already elevated production costs, such as the pulp sector, undergo a comparatively lower relative cost increase, despite encountering a similar absolute cost increase (see Figures 3b and 5b). In addition, it is interesting to note which cost components are the dominant contributors to the cost increase resulting from CCS implementation. For all industries, the transportation and storage costs of CO_2 constitute a substantial proportion of the cost increase, accompanied by an increase in operating expenditures and annualised capital expenditures. It can also be noted that the CAPEX for the CCS unit in general represents a rather small share of the total cost increase (see Figure 5a–e). The refinery fuel production cost (see Figure 5e) constitutes to a large extent of the costs for the raw material, crude oil, and waste bio-oils. To reduce costs and identify suitable business models, a comprehensive analysis of these distinct cost components is crucial.

This economic analysis results in CO_2 capturing costs, excluding the costs for transportation and storage of CO_2, for each separate industry according to Table 3.

Table 3. CO_2 capturing costs for the four basic commodity industries, excluding CO_2 transportation and storage costs.

Industry	**Cement**	**Pulp**	**WtE**	**Refinery**	
CO_2 capture cost excl. transportation and storage	77	73	91	89	€/tCO_2

Figure 6 shows an analysis of the break-even EU ETS allowance price for the reference case compared to the CCS case. The analysis shows that at allowance prices of 139 and 230 €/tCO_2 CCS become competitive for the cement and the fossil-based refinery sectors, respectively. However, for the WtE sector, only one-third of the emissions are fossil-derived, meaning that a rather high allowance price is needed to break even. Thus, to render this investment economically feasible, the negative emissions (two-thirds of the total emissions) should be sold on a separate carbon market (CM), when such a market is available. Assuming that there is a market for negative-emissions certificates and that these can be sold at a price equal to the allowance price, the CCS case for WtE breaks even at 135 €/tCO_2. It seems reasonable to assume that any market or incentives for biogenic CCS would not assign a value to negative emissions that is higher than the cost to emit fossil CO_2.

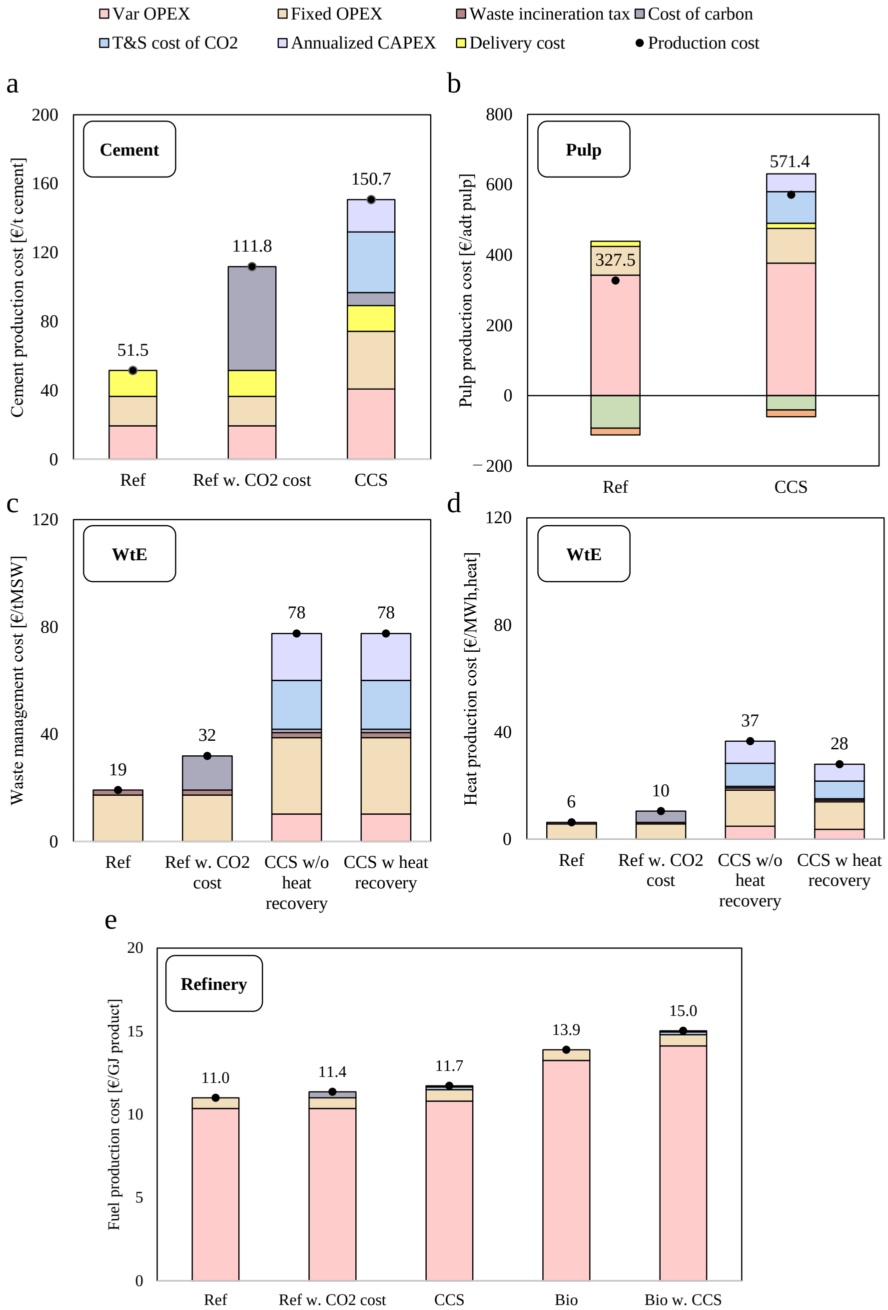

Figure 5. Break-down of the commodity production costs for: (**a**) Cement, (**b**) pulp, (**c**,**d**) WtE (waste management cost and heat production cost respectively), (**e**) refinery.

3.2. Life-Cycle Emissions

Table 4 shows the calculated emissions factors for each commodity and end-use for the reference and CCS cases, respectively. The EF column shows the total emissions factor, which is the sum of the fossil emissions and negative emissions, i.e., obtained when CCS is applied to biogenic emissions (as indicated above, the biogenic emissions are regarded as zero emissions when emitted to the atmosphere). For the cement, pulp, and WtE plants, the carbon footprint for the basic commodity is decreased drastically by up to 90% depending on the configuration. This is largely due to the fact that the up-stream emissions associated with extraction of the raw material (limestone, pulpwood, and waste handling) for the basic commodity plant represent a rather small share of the total carbon footprint. However, as mentioned above, the refinery has rather large up-stream emissions associated with crude oil and NG extraction and transportation, which cannot be reduced using CCS, and the carbon footprint associated with the fuel production is, therefore, not reduced significantly. A similar reasoning applies to the plastic products incinerated in the WtE plant (see Appendix A Figure A2). For further details and the life-cycle emissions break-down for each end-use, see Appendix A Figures A1 and A2.

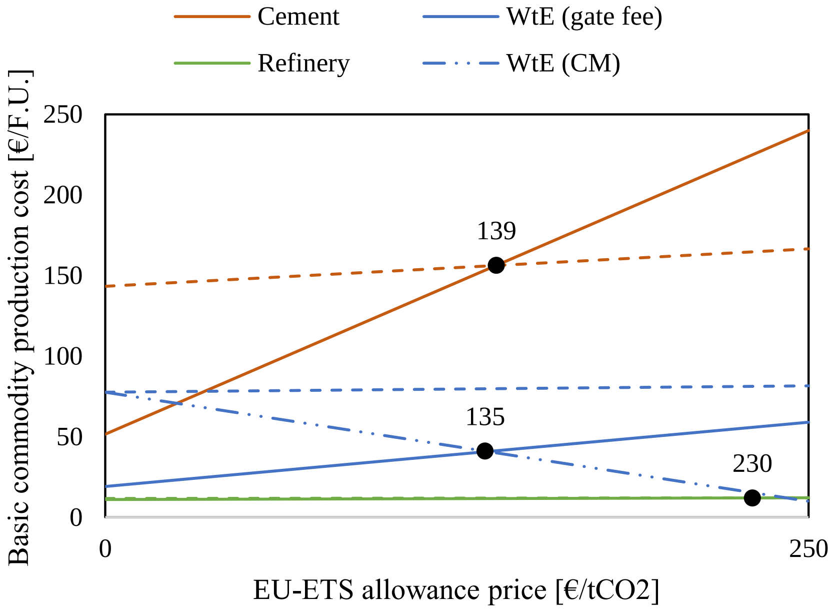

Figure 6. EU ETS allowance prices for situations in which the commodity production cost is the same for the reference case (whole lines), which pays for allowances, and the CCS case (dashed line). The production cost for WtE is shown for the gate-fee, and WtE (CM) represents the case in which negative emissions are sold on a separate carbon market.

Table 4. Calculated life-cycle emissions for each commodity and case.

	Commodity	**Case**	**EF**	**Biogenic Emissions**	**Negative Emissions**	
Cement	Cement	Ref	0.75	0.05	-	tCO_{2eq}/t cement
		CCS	0.09	0.01	0.05	tCO_{2eq}/t cement
	Concrete	Ref	0.35	-	-	tCO_{2eq}/m^3 concrete
		CCS	0.08	-	-	tCO_{2eq}/m^3 concrete
Pulp	Pulp	Ref	0.10	2.72	-	tCO_{2eq}/ADt pulp
		CCS	−2.0	0.61	2.11	tCO_{2eq}/ADt pulp
WtE	Heat	Ref	0.05	0.10	-	tCO_{2eq}/MWh_{heat}
		CCS w. heat recovery	−0.12	0.015	0.13	tCO_{2eq}/MWh_{heat}
		CCS w/o heat recovery	−0.09	0.011	0.10	tCO_{2eq}/MWh_{heat}
	Waste management	Ref	0.19	0.35	-	tCO_{2eq}/t MSW
		CCS w. heat recovery	−0.28	0.035	0.32	tCO_{2eq}/t MSW
		CCS w/o heat recovery	−0.28	0.035	0.32	tCO_{2eq}/t MSW
Refinery	Products	Ref	12.2	-	-	$kgCO_{2eq}/GJ_{product}$
		CCS	9.2	-	-	$kgCO_{2eq}/GJ_{product}$
		Bio	10	0.87	-	$kgCO_{2eq}/GJ_{product}$
		Bio-CCS	7.8	0.10	0.77	$kgCO_{2eq}/GJ_{product}$

4. Discussion

From the results of the present work as well as previous studies, it is clear that investing in high-abatement measures, such as CCS, has major impacts on basic commodity production costs, whereas the impacts on down-stream costs (as well as price, since we have included certain profit margins, as defined in Table 2) appear to be weak, even though the emissions reduction potential are substantial. This refined and expanded analysis agrees with previous research (see, e.g., [8–11]). Furthermore, it should be noted that even though the case studies in this work have been applied exclusively to the CCS technology, the methodology used and the outcomes of the analysis are transferable to any kind of high-cost abatement measure that could be implemented in basic commodity industries, for example hydrogen-based steel production. Future work could include other product value chains with different characteristics as well as other industries such as the steel industry.

4.1. Low-Carbon Products and Added Value

Other important aspects are market competition and the extent to which offering low-carbon products will confer a competitive advantage. If the CCS-produced commodity is to be sold at a higher price than a non-CCS-produced commodity, this suggests that it must have some added value. However, if one disregards the production step, the two commodities are identical (having the same properties), so the added value of using CCS is only via emissions reductions. While an added value is typically connected to economic returns, it could also provide ecological and/or social value together with economic value [43]. Added value in the form of emissions reductions could lead to an increased willingness to pay for consumers, meaning that the commodity could be sold at a premium price compared to the conventional product, which would entail higher revenue for the producer.

Moreover, CCS-produced commodities will face market barriers, such as being exposed to competition from non-CCS-produced commodities or being replaced with other types of commodities or other mitigation measures [44]. Examples of this are cement in a building being replaced with wood or lighter construction materials, or DH as a heating solution in a villa being replaced by an individual heat pump. Thus, if there is no possibility to earn a premium for low-carbon products, they may result in losses. Naturally, the magnitude of this market risk depends on the commodity and the existence of alternative solutions, as well as on the development of carbon pricing systems, such as the EU ETS. As a result of the previously mentioned *Fit for 55* package with the revision of the EU ETS system, the price of emission allowances is likely to increase which, together with the phase out of free allocations, may result in allowance prices that are well in parity with the cost of CCS.

4.1.1. Profit Margins and Full Cost Pass-Through

Clift et al. have suggested that "the ratio of environmental impact to economic value decreases markedly along the supply chain" [45], meaning that the strongest environmental impact is linked to the commodity production, albeit with only a small added value, while the opposite phenomenon occurs down-stream of the chain where substantial value is added at a lower environmental cost. Consequently, profit margins tend to be smaller in the beginning of the value chain and larger in the later stages. This is closely linked to the assumption of full cost pass-through and the extents to which different industries can transfer costs through the value chain. However, the extent to which this can be accomplished varies between industries and depends on several factors, such as market structure, demand, market power, and competition. For example, a company with greater market power might have greater opportunities to absorb cost shocks and, thus, have the prerequisites for full cost pass-through [46]. In contrast, if the competition is hard, the profit margin of the firm may be low, such that even a small increase in the production cost will have a significant impact on the profit margin. For example, the refinery sector is highly exposed to market risks, and even though the cost increment is low for truck transportation and air-freight, the cost increase at the fuel pump is significantly higher. The prospects for motivating consumers to choose these lower-carbon fuels without any incentives or policy interventions will depend greatly on consumer preferences. Moreover, the fuel production cost for the refineries is highly dependent upon the cost for feedstock materials (e.g., crude oil or waste-oils), and with their profit margin being rather low, there is only a narrow window of opportunity to absorb external costs. This points to the importance of a strong climate policy that incentivises mitigation measures.

4.1.2. Comparison of Industries and Cross-Value Chain Collaboration

Depending on the properties of the basic industries and associated value chains, the possibilities to transform the value chain may differ. These possibilities will reflect the following: the market on which the commodity is traded (nationally or internationally); the identity of the end-consumer (governmental actor or private consumer); and the cost structure of the basic commodity (cheap bulk products will experience an even larger relative cost increment than more-expensive basic commodities). Governmental actors (e.g., national road administrations) often have clearly defined targets in line with governmental climate targets (for example, net-zero emissions by Year 2045 for Sweden) and, thereby, have the opportunity to engage in green public procurement to comply with those targets. Governmental actors might have a greater opportunity to internalise the increase in the cost of the low-carbon commodities to benefit the commons if this contributes to national climate targets. In this manner, the cost of emission reductions is shared among all citizens, since the state pays for the emission reductions by purchasing, for example, low-carbon cement with tax-payer's money. This deviates from the 'polluter pays' principle, whereby the polluter (cement industry) rather than Society (the citizens) should pay for the emissions reductions. However, the pulp industry, for example, might not experience the same benefits, as pulp is an internationally traded product and being a component in a wide variety of bulk consumer products, such as diapers, toilet paper, moving boxes, etc. The pulp industry might, therefore, experience higher market barriers due to competition and would be reliant on the willingness of private consumers to pay for climate-positive products (although the results from the present study show that the cost would increase only marginally). On the other hand, the pulp industry might also be able to use market segments that contain consumers with low price sensitivity (meaning that demand changes to a small degree when the cost of the product increases) and with other customer values, such as valuing decreased climate impact. It is inevitable that the basic commodity producer is the actor taking on the greater risk when investing in high-cost abatement measures. To mitigate some of these risks and to spread the risk across all actors in the value chain, cross-value chain collaboration and long-term agreements will most likely be needed. If the findings from this study were to be applied so that risk could be moved from the basic commodity producer and shared along the value chain, it could encourage adoption of high-cost abatement technologies in major emitting industries. However, there are challenges with reaching full cost passthrough and research is needed to investigate whether this is achievable through voluntary agreements or if policy interventions are needed.

4.2. Policies and Business Models for Negative Emissions

Policy models, such as state guarantees through reversed auctioning, could be used to incentivise and create markets for negative emissions [47]. This type of policy model can be motivated by the fact that producing negative emissions incurs a cost for the emitter who mitigates the biogenic emissions, whereas the benefits are shared by all. Yet, it is reasonable to assume that in the longer run a market for negative emissions should be developed that involves sectors with emissions that are hard to abate, e.g., in the form of quota obligations or voluntary carbon markets (VCM). There is also a need for the EU to introduce some type of CO_2 removal credit system [48], so as to comply with the proposed targets for climate neutrality by Year 2050 [49]. VCM could be used by basic commodity producers that are creating negative emissions. Instead of linking the negative emissions to the commodity, they could be sold at the VCM, thereby generating further revenues.

5. Conclusions

This work shows that when the cost for CCS implementation is distributed along the product value chain assuming full cost pass-through it potentially imposes a small cost increase on end-consumers, assuming that the end-product producer can maintain a sufficiently large profit margin. While the cost increases only marginally for the end-user (0.3–3.3%), the related emissions are reduced by up to 36%. The magnitude of the cost increase for the end-product naturally depends on the specific end-use and what share of the cost the basic commodity represents. However, the same trends are seen regardless of the industry or end-use considered in the present work. Naturally, the methodology used and the outcomes of this analysis are transferable to any type of high-cost abatement measure in the basic commodity industry, and are not limited to just CCS. For example, the same methodology could be used for hydrogen-based steel production (which is estimated to be around 15–100% more costly than conventional steel production [50]). Moreover, intermediary actors in the value chain could play key roles as enablers of the transition, due to the significant drop in cost increment that occurs already for these actors.

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Appendix A.

Appendix A.1. Commodity Costs and Prices

Table A1 shows the costs and prices for other raw materials that are needed and by-products that are produced during basic commodity production.

Table A1. Other commodity costs and prices for raw materials and by-products in basic commodity production.

Commodity	Cost/Price	Unit	References
Cement chain			
Limestone	3	€/t	[9]
Pulp chain			
Round wood	40	€/m^3	[6]
Tall oil pitch	500	€/t	[14]
WtE chain			
Plastic bag [b]	0.67	€/bag	[51]
Butter package [b]	2.7	€/butter package	[52]
Refinery chain			
Crude oil	61.4 [a]	US$/barrel	[53]

[a] Average crude oil price in Year 2019. [b] Assumed average price on the Swedish market.

Appendix A.2. Cement Chain

Cement production generates both fuel-based and process-based emissions from the calcination process in the lime kiln. The process-based emissions account for approximately two-thirds of the total emissions and occur due to the decomposition of carbonate material that originates from the input raw material, limestone. The cement plant has an assumed production capacity of 1.5 Mt of cement per year. The thermal energy requirement in the cement kiln is assumed to be 3025 MJ per tonne of cement clinker [9]. For further details on the assumed fuel mix, see Table A2.

Table A2. Assumed thermal energy requirement and fuel mix for cement production.

Cement Plant Specifications				
	Thermal energy requirement *	3025	MJ/t cement	[9]
Fuel mix				
	Coal	49	% of energy supplied	[54]
	Petcoke	23	% of energy supplied	[54]
	Fuel oil	1	% of energy supplied	[54]
	Alternative fuel [a]	15	% of energy supplied	[54]
	Biomass	11	% of energy supplied	[54]

* In the cement kiln/precalciner. [a] Assuming 40% biomass-based.

Cement is a bulk product that is commonly used in large infrastructure or building projects. In this work, a high-speed railway is studied as an end-product, with the National Transport Administration as the consumer. Cementitious materials account for approximately 45% of the total cradle-to-gate life-cycle emissions of the railway. The concrete used in the construction is assumed to be ready-mix concrete (RMC), with a cement content of 18 wt%. For details of the specific properties, such as the material composition of the railway, see Table A3. The material composition of the high-speed railway was acquired via personal communication with the Swedish Transport Administration.

Table A3. Assumed material composition (in wt%) of the high-speed railway.

Material Composition	**Material Used in the Railway**			**Emissions Factor**		
Concrete	83	wt%	[55]	-	$tCO_{2,eq}/m^3_{concrete}$	Own calculations
Steel products *	5	wt%	[55]	-	$tCO_{2,eq}/t_{steel}$	ecoinvent database
Asphalt	4	wt%	[55]	-	$tCO_{2,eq}/t_{asphalt}$	ecoinvent database
Cement	3	wt%	[55]	-	$tCO_{2,eq}/t_{cement}$	Own calculations
Additional limestone	2	wt%	[55]	-	$tCO_{2,eq}/t_{limestone}$	ecoinvent database

* Rails, construction steel, and reinforcement steel.

Appendix A.3. Pulp Chain

The Kraft pulp mill has three main point emission sources: the recovery boiler, the lime kiln, and the multi-fuel boiler (also referred to as the 'power boiler' or 'bark boiler'). The pulp mill has an assumed production capacity of 0.8 M air-dried tonne (ADt) pulp per year, with the raw material assumed to be pine and spruce (50%/50%) [14]. In addition to producing pulp, the mill is co-producing crude tall oil and electricity, both of which are sold on the market, thereby generating an income for the mill. As mentioned previously, the biomass used in the mill is assumed to have been produced through forest management that maintains the carbon stock of the forests, meaning that the electricity and heat produced are considered to be carbon-neutral in the reference case.

Pulp is commonly used in bulk private consumer products, and the end-product considered here is a disposable diaper for a baby. Fluff pulp is a major constituent of the diaper, accounting for approximately 32 wt% of the final product. For the specific properties of the diaper, such as the material composition which is taken from [56], see Table A4.

Table A4. Disposable baby diaper material composition and related emissions factors.

Material Composition	Material Use per Diaper			Emission Factor		
Fluff pulp	12.7	g	[56]	-	$kgCO_{2,eq}/kg$	Own calculations
Non-wovens	9.53	g	[56]	-	$kgCO_{2,eq}/kg$	ecoinvent database
LDPE film	18.8	g	[56]	-	$kgCO_{2,eq}/kg$	ecoinvent database
Elastics	0.02	g	[56]	-	$kgCO_{2,eq}/kg$	ecoinvent database
SAP	15.15	g	[56]	-	$kgCO_{2,eq}/kg$	ecoinvent database
Adhesive	0.95	g	[56]	-	$kgCO_{2,eq}/kg$	ecoinvent database

LDPE, low-density polyethylene.

Appendix A.4. WtE Chain

Incineration of waste in WtE plants is one way to handle municipal solid waste (MSW), and around 27% of all MSW generated in the EU-27 in Year 2021 was incinerated [57]. CCS is a possible abatement measure to reduce emissions in the WtE sector. However, in this particular sector, it is not straight-forward to define the conditions under which CCS can be regarded as a 'sustainable' mitigation measure, since it will continue the linear use of carbon atoms as resources, while there are possibilities for chemical recycling of the waste, which would be more in line with the EU's Waste Framework Directive [58]. Other technologies, such as thermo-chemical recycling technologies [59], could enable the circular use of carbon atoms within Society. However, since the WtE system is already in place today and CCS is part of the climate road map of the sector according to CEWEP [60], the effects of CCS on WtE are assumed to be of relevance, justifying their exploration in the present work. In addition, even if thermo-chemical recycling is applied, part of the process can involve CO_2 capture from future incinerators if these are integrated into the thermo-chemical recycling process.

The WtE plant studied is a CHP plant that provides the following three services: waste management; heat to the DH network; and electricity to the grid (see Figure 2). The incoming waste is of both fossil and biogenic origin, accounting for one-third and two-thirds, respectively, of the total [30], with the fossil-derived fraction largely consisting of plastics. The plant handles 535 kt of MSW yearly.

Two types of end-uses were considered: housing and plastic products (Figure 1). Households use several different utilities, such as heat, electricity, water, and waste management services. The heat demand from housing is in this work assumed to be supplied through DH. Since the households are using several of the services provided by the WtE plant, their monthly living costs are affected in several ways. Since not all the incoming waste originates directly from households, but some also from other municipal waste collection systems, one could consider loading the additional cost of CCS onto the extended producer responsibility. Thus, the producer would include the additional cost of waste handling in the price set for the product. In this work, two plastic products are considered using this principle: a plastic carrier bag and food packaging in the form of a butter package. The plastic carrier bag is composed completely of plastics, while the plastic in the butter package represents a much smaller share of the total product, which also includes the butter itself. For detailed information about the products, see Table A5.

The cost of housing for the reference case is based on the average rental apartment in the Gothenburg region, as obtained from Statistics Sweden [61–63].

The utility usages in the household are assumed according to Table A5.

Table A5. Assumptions regarding the housing end-use: utility use per household and year and associated emissions factor per utility.

Housing Utility Use per Year	Use per Household and Year			Emissions Factor		
Waste	461.5	kg	[64]	-	$tCO_{2,eq}/tMSW$	Own calculations
Heat	9300	kWh	[65]	-	$tCO_{2,eq}/kWh_{heat}$	Own calculations
Electricity	6925	kWh	[66]	0.365	$tCO_{2,eq}/kWh_{el}$	Swedish Environmental Protection Agency [67]
Water	4378	m^3	[66]	-	$tCO_{2,eq}/kg$	ecoinvent database

Table A6 shows the assumed material compositions of the two plastic products (plastic carrier bag and butter package) investigated.

Table A6. Plastic products (plastic bag and butter package): assumptions and compositions.

		Composition		
Plastic bag				[68]
Plastics (LDPE)				
	Weight	41.66	g	
Butter package				
Plastics				[69]
	Weight	250 (52)	g	

Appendix A.5. Refinery Chain

A refinery produces multiple products, and in this study, the products are assumed to be fuels for transportation, such as diesel, petrol, and jet fuel. Conventional refineries process a fossil feedstock, i.e., crude oil. The refinery emissions usually account for a small share of the total life-cycle emissions of a fuel. Up-stream emissions related to crude oil and NG extraction are substantial compared to the refinery emissions, as the process has a rather high feedstock-to-product efficiency rate, which in this work is assumed to be 89% [25]. However, the largest share of emissions is related to the combustion of the fuel in the use phase. This fact makes this industry different than the others studied in this work. Since the refinery emissions only account for a small fraction of the total life-cycle emissions, implementing CCS at the refinery will have a weak impact on emissions reductions for the fuel. Therefore, other mitigation measures, such as feedstock switching, must be implemented to have a stronger impact on fuel-related emissions. Currently, the dominant production of biofuels is through the processing of waste bio-oils to produce hydro-treated esters and fatty acids (HEFAs). The availability of waste oils is limited but the HEFA route can also use other feedstocks, such as vegetable oils, although these alternatives may raise sustainability concerns [70]. Waste bio-oils would need to be imported to meet the quantities required by the refining industries, leading to a need to replace the current application of such oils with alternative feedstocks, thus potentially resulting in carbon leakage from one industry to another. Other biorefinery concepts are emerging using other feedstocks that comply with the EU's definition of advanced biofuels, i.e., feedstocks listed in the EU Renewable Energy Directive [71]. However, in this work, a conventional oil refinery processing a fossil feedstock is used as the reference case, with an additional case that assumes the replacement of 20% of the fossil feedstock with waste bio-oils, in this case Used Cooking Oils (UCO).

The end-uses studied in this work are related to fuel use in the transportation sector. Some parts of the transportation sector are easier to decarbonise than others, such as passenger vehicles using electrification. However, other segments, such as heavy-duty vehicles and aviation, face greater challenges. One way to decarbonise these sectors is through replacing fossil fuels with biofuels. In 2021, the EU proposed a policy whereby jet fuel suppliers need to blend renewable jet fuels with fossil jet fuels [72]. The proposed target is a renewable share of 5% in Year 2030, increasing to 63% in Year 2050. The renewable share is further divided into biofuel and synthetic fuels. HEFA is already used in the aviation sector but currently accounts for only 0.5% of total jet fuel demand [70]. Moreover, due to aviation being operated across national borders and the complexity of such policy measures, the sector has so far been exempt from excise duty [73], although the sector is now included in the EU ETS. Similarly, heavy-duty vehicles, such as trucks and buses, account for more than 6% of EU GHG emissions, and the EU has proposed targets to reduce sector-related emissions by 45% up to Year 2030 and by 90% up to Year 2040, relative to the emissions levels in Year 2019 [74].

Cost structure for the end-uses of air-freight and truck transportation is assumed according to [75]. Up-stream emissions related to crude oil and natural gas extraction and transportation are adapted from [76].

Appendix A.6. Life-Cycle Emissions

In the following section, more detailed results are presented for the life-cycle emissions for intermediary commodities and end-uses.

Appendix A.6.1. Intermediary Commodities

Figure A1 shows the detailed life-cycle emissions for the intermediary commodities of concrete and district heating.

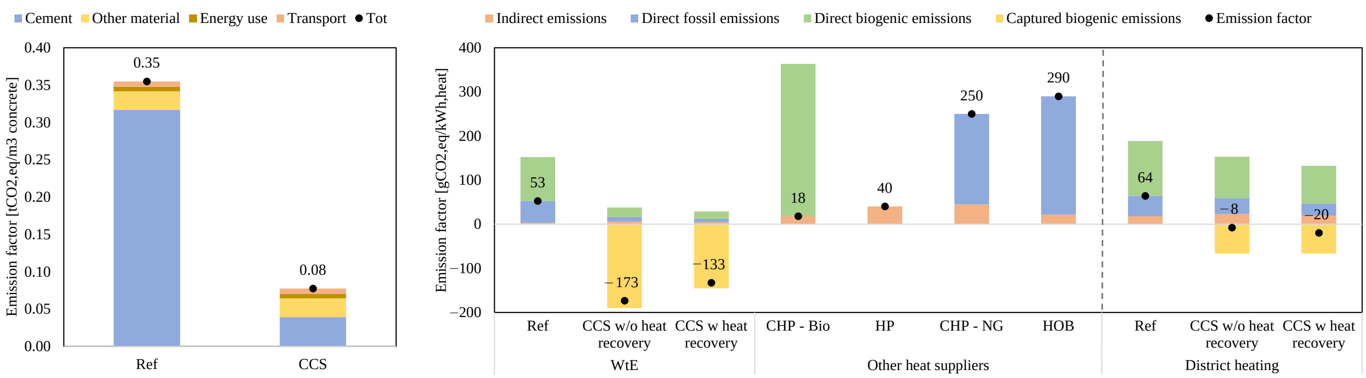

Figure A1. Detailed results regarding the life-cycle emissions for the intermediary commodities of concrete and district heating.

Appendix A.6.2. End-Uses

Figure A2 shows a more detailed breakdown of the emissions posts (shown as relative emission reductions) from the LCA results for the end-uses investigated for each industry.

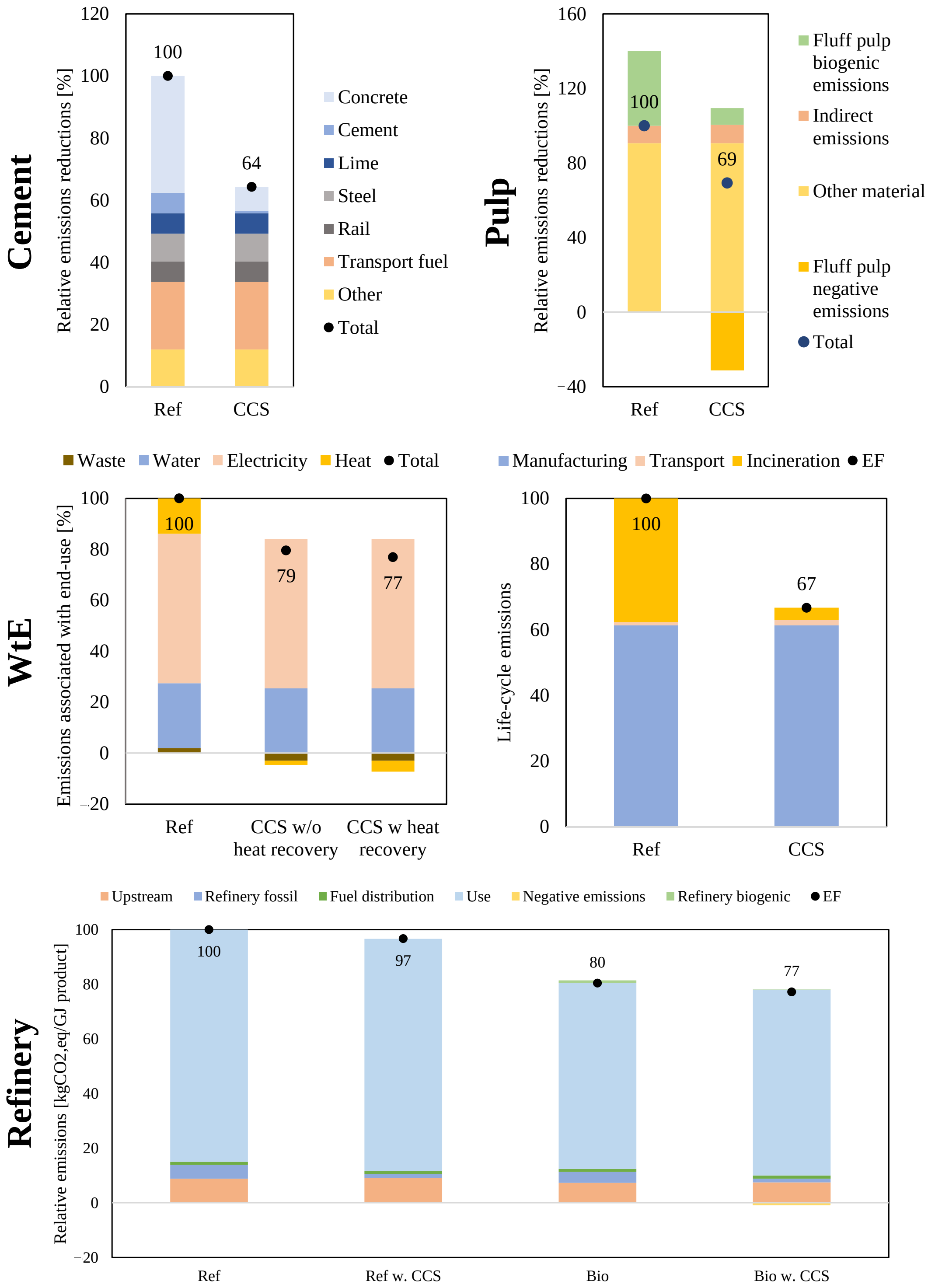

Figure A2. Detailed breakdown of the emissions posts (shown as relative emission reductions) from the LCA results for the end-uses investigated for each industry.

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