THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Blueprint for the deployment of capital-intensive technologies for the decarbonisation of energy-intensive industries

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Abstract

Emissions associated with industrial processes account for approximately one-fourth of the territorial greenhouse gas (GHG) emissions in the European Union (EU). A broad portfolio of mitigation measures is needed to meet the EU's climate target of net-zero GHG emissions in Year 2050. On the supply side, transformative mitigation options, such as carbon capture and storage (CCS) and hydrogen direct reduction (H-DR), are necessary for mitigating carbon emissions from energy-intensive industries that produce basic materials. Yet, there are currently no full-scale, fully operational plants producing iron and steel, cement or chemicals with near-zero emissions anywhere in the world. Thus, this work focuses on the large-scale implementation of capital-intensive technologies, using as examples the application of CCS in various basic materials industries and indirect electrification of the steel-making process via H-DR.

This work explores the implementation of capital-intensive technologies through a techno-economic assessment using a value chain perspective that extends from basic materials to end-products. A novel approach, the Value Chain Transition Fund (VCTF), is proposed to finance the investments required to accelerate the transition towards zero-emissions practices. This study also considers the policy and infrastructure aspects outside the plant boundaries that are necessary for the deployment of these technologies.

The results show that while low-carbon basic materials face market barriers, due to being significantly more expensive and having to compete with cheaper carbon-intensive-materials, the incremental cost increase for related end-products is small. By leveraging this principle, the VCTF can help to address market and investment barriers. Furthermore, while the EU ETS is a key policy instrument driving the transition, relying solely on carbon pricing will not guarantee a successful and timely transition. It is concluded that complementary measures, such as the VCTF, are needed to mitigate the financial risk associated with decarbonising capital-intensive industries. This work also illustrates the importance of having complementary policy measures and a technology-specific regulatory framework in place to enable the transition.

Keywords: Industry; Basic material, Decarbonisation; Capital-intensive technologies; CCS; H-DR

List of publications

The thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. Hörbe Emanuelsson, A., Rootzén, J., Johnsson, F. Deployment of Carbon Capture and Storage in the cement industry – is the European Union up to shape? *Manuscript.*

II. Hörbe Emanuelsson, A., Johnsson, F. The Cost to Consumers of Carbon Capture and Storage — A Product Value Chain Analysis. *Energies* **2023**, *16*, 7113. https://doi.org/10.3390/en16207113

III. Hörbe Emanuelsson, A., Rootzén, J., Johnsson, F. Financing high-cost measures for deep emission cuts in the basic materials industries — proposal for a Value Chain Transition Fund. *In review.*

Anna Hörbe Emanuelsson is the principal author of all the papers. Professor Filip Johnsson contributed with discussions, methodology development and editing to **Papers I-III**. Dr. Johan Rootzén contributed with discussions, methodology development and editing to **Papers I** and **III**.

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Anna Hörbe Emanuelsson
Göteborg, October 2024

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1 Introduction

In Year 2022, energy-intensive industries accounted for 22% of the European Union's (EU's) annual territorial greenhouse gas (GHG) emissions (European Commission, 2023c). The EU has ambitions to reduce GHG emissions to net-zero by Year 2050 according to the European Green Deal (European Commission, 2021), to which all 27 EU Member States are committed. Within the Green Deal, the *Fit for 55* initiative mandates a reduction of the EU's net GHG emissions by at least 55% by Year 2030, as compared to the Year 1990 levels, and climate-neutrality by Year 2050 (European Commission, 2023b). Meeting these targets will require ambitious and rapid measures for the mitigation of GHG emissions across all sectors of the economy – creating a substantial demand for materials and services that have low or no climate impacts.

Many of the energy-intensive industries are also emissions-intensive in terms of CO_2 and are known as "hard-to-abate", meaning that it is deemed challenging to mitigate GHG emissions in these industries with respect to high investment costs, but also that decarbonisation typically requires the application of technologies and processes that have not been previously applied at scale. Mitigation measures include energy efficiency measures, material substitutions, fuel switching, and various circular economy and sufficiency measures. Along with these more-incremental measures, transformative technology options, such as Carbon Capture and Storage (CCS) and direct and indirect electrification, which involve complete replacement of existing processes, will be needed to enable deep emission cuts. Each measure has a different cost structure, in terms of the overall cost and the distribution of investment costs and operational costs, whereby incremental measures conventionally imply lower total costs compared to transformative technologies. A broad portfolio of decarbonisation options will most likely be required to succeed with the transition to near-zero or net-zero emissions. However, the transformative technology options present a more-significant challenge for implementation, which make it more difficult to overcome barriers compared to the incremental mitigation options. Therefore, this work focuses specifically on the large-scale implementation of capital-intensive technologies, using the examples of CCS in a range of industries and indirect electrification of the steel-making process using the hydrogen direct reduction (H-DR) technology.

The CCS technology has been available and in use in specific contexts for decades, with the complete chain of processes — from CO_2 capture to transportation and storage — now being

commercially available. However, it is not known when any large-scale deployment of the technology will take place. The conditions under which the carbon-intensive industries are able to realise capital-intensive mitigation measures reflect a variety of factors, ranging from the purely technical to economic, political and market aspects. The more-technical aspects of capturing CO_2 are relatively well-researched, whereas several landscape factors remain to be addressed. These factors include: markets and demands for low-carbon products; the supporting infrastructure (i.e., to transport and store CO_2 and electricity grid for the production of green hydrogen); the acquisition of financing; related policies to incentivise and enable the transition; and societal acceptance. This work explores some of these conditions and their impacts on the implementation of capital-intensive technologies for deep mitigation in carbon-intensive industries.

1.1 Aim and scope

The overall aim of this thesis is to explore the conditions for EU's carbon-intensive industries to implement capital-intensive technologies (i.e., CCS and H-DR), in order to meet climate targets in a timely manner. This work evaluates the key techno-economic, financial, market and political landscape factors for the rapid deployment of capital-intensive technologies that are urgently needed to achieve deep decarbonisation. The thesis addresses the following issues:

- Policy and infrastructure oriented conditions outside plant boundaries that are necessary for the deployment of capital-intensive technologies;
- The cost to consumers of capital-intensive technologies from the product perspective; and
- Financing of capital-intensive mitigation technologies using a novel approach: the Value Chain Transition Fund.

1.2 Outline of the thesis

This thesis consists of this summarising essay and the three appended papers. This essay highlights the key outcomes of the papers and places the work in context. Following the introductory chapter, Chapter 2 gives some background to the work, while Chapter 3 briefly describes the key methodologies used. Chapter 4 highlights selected results connected to the above-mentioned aims, which are thereafter discussed in Chapter 5. Chapter 6 offers conclusions from the work, and Chapter 7 proposes some future work.

For the three main topics analysed in this thesis, different industries and capital-intensive technologies are used as case studies to exemplify the principles.

The first aim is addressed in **Paper I**, which explores the techno-economic uncertainties linked to CCS implementation, the availability of and prospects for a supporting infrastructure for transporting and storing CO_2, as well as the development of a legislative context across the EU for the deployment of CCS in the cement industry of the EU-27 Member States.

The second aim is addressed in **Papers II** and **III**, which illustrate the impacts on the costs to consumer of end-products when CCS and H-DR are applied as deep mitigation measures in the basic commodity industries. This analysis takes a techno-economic perspective from basic commodity production to end-product consumption using a product value-chain analysis and Life-Cycle Assessment (LCA).

The third aim is addressed in **Paper III**, which focuses on the financial aspects of implementing capital-intensive technologies. A novel approach to financing capital-intensive technologies (CCS and H-DR) in the cement and steel industries is proposed that aims to share the financial risk for financing the investments required to accelerate the transition towards zero-emissions operations in the basic materials industries. Towards this goal and to engage non-State actors in the process, as well as to formalise cross-sectorial collaboration, the establishment of a Value Chain Transition Fund (VCTF) is explored.

Figure 1 provides an overview of the topics, decarbonisation technology, and industries covered in each paper.

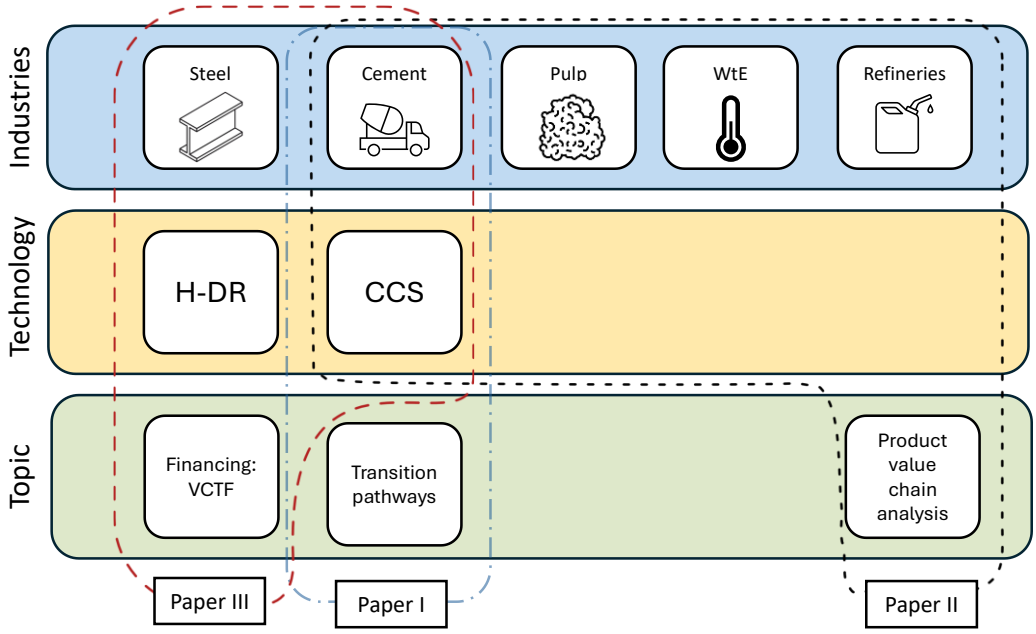

Figure 1. Overview of the topics covered and the linkages between the papers appended to this thesis. CCS, Carbon Capture and Storage. H-DR, hydrogen direct reduction.

2 Background

The following sections provide some contextual background information on the topics of: *Mitigation of industrial CO_2 emissions and the role of the CCS technology* (Section 2.1), *Non-technical barriers to the implementation of capital-intensive technologies* (Section 2.2), *Policy options for decarbonisation* (Section 2.3), *Demand for materials* (Section 2.4), and *Financing capital-intensive technologies* (Section 2.5).

2.1 Mitigation of industrial CO_2 emissions and the role of the CCS technology

This work focuses on the following industries: cement, steel, pulp, waste-to-energy, and refineries. Each industry has a distinct portfolio of mitigation options that they can apply to abate emissions, ranging from incremental to transformative technology options. The extents to which these industries can rely on different mitigation options vary depending on the nature and complexity of the specific industry. This work explores the decarbonisation of the current production processes rather than exploring a complete overhaul and transformation of the economic system. Some industries have more-advanced and defined pathways for future decarbonisation, whereas the future for others appears more uncertain. The following sections provide further descriptions of the mitigation measure portfolios for the studied industries.

2.1.1 Cement industry

In cement production, around two-thirds of the total emissions are inherent to the cement-making process (process emissions), making them difficult to abate. The remaining one-third of emissions is associated with fuel use. Currently, the EU cement industry largely relies on fossil and alternative fuels. To mitigate the fuel-related emissions, the fossil fuels should be phased out through switching to non-fossil fuels or the process could be electrified [however, electrification of the cement-making process has a lower Technology Readiness Level (TRL)] (International Energy Agency, n.d.). Thus, energy use-related fossil emissions could be decreased, assuming that the electricity used has a low emissions factor in the case of electrification. To mitigate the emissions inherent to the process, CCS with a high capture rate is the main mitigation option. Cement constitutes cement clinker, aggregates and water. The cement clinker production is the major source of emissions, so by substituting the cement clinker with alternative binders, the emissions related to cement could also be decreased (Shah et al., 2022). However, in those sectors in which cement is being used (i.e., buildings and infrastructure), the currently applied standards do not allow for high substitution rates.

2.1.2 Steel industry

Most primary steel is produced in large-scale, integrated steel mills that rely heavily on fossil fuels to reduce the iron ore. In general, the steel industry has, compared to the cement industry, a more-complex plant design and commonly utilises multiple stacks. Using CCS to achieve significant emissions reductions is, therefore, more complex, and it seems likely that CCS would only be applied to a share (50-80%) of the emissions (see for example IEAGHG (2018) and references therein), which means that it would not achieve near-zero emissions. While emissions could also be reduced by replacing fossil fuels with renewable fuels (reduction levels of 38%–55%) (Mandova et al., 2019; Tanzer et al., 2020), there will likely be a high demand and strong competition for renewable combustible fuels in the future. Instead, many European steel producers have announced that they are going to implement direct reduction of iron using hydrogen (H-DR) in the long-term, preferably using hydrogen that is produced using renewable energy sources, so as to ensure a low carbon footprint. Using so-called "blue hydrogen" (i.e., hydrogen from natural gas from which the CO_2 has been captured and stored underground) is also a possibility (Eurofer, 2022).

The production of secondary steel in electric arc furnaces results in a much lower intensity of emissions per tonne of product, as compared with primary steel production. Replacing the demand for primary steel production and increasing the use of secondary steel represent a viable approach to lowering emissions across the sector. However, the use of scrap steel as feedstock is a limited resource. Primary and secondary steels possess distinctly different qualities and grades, making them suitable for different applications. Thus, contractors involved in construction should consider product selection carefully and substitute primary steel with secondary steel wherever and whenever it is feasible to do so (Karlsson et al., 2020).

2.1.3 Pulp industry

While there are several pulp production processes, the dominate one, corresponding to 80% of total pulp production in the EU, is the chemical pulp process (Cepi, 2023). The pulping industry is a major emitter of biogenic CO_2 and the chemical pulp industry in the EU-27 countries has a significant share of the biogenic emissions. By implementing CCS in the pulp mill, Carbon Dioxide Removal (CDR) can be achieved, provided that the biomass feedstock is sourced from a system in which the carbon stock is at least maintained or exhibits a net growth (for example, a well-developed forest management system). Kraft pulp mills commonly have three main stacks, and depending to which of these stacks CCS is applied, different levels of CDR can be achieved (Rosa et al., 2021).

2.1.4 Waste-to-Energy

Waste-to-Energy (WtE) plants are predominantly concentrated in the northern parts of the EU. The waste combusted is typically municipal solid waste and has both fossil and biogenic contents; in Sweden, for example, the municipal waste is on average one-third of fossil origin and two-thirds of biogenic origin. Thus, CDR can be attained by implementing CCS in the WtE plant. It is important to note that CCS can only achieve a continued linear use of carbon atoms, whereas other technologies, such as thermo-chemical recycling technologies or Carbon Capture and Utilisation (CCU), enable the circular use of carbon atoms within Society. However, that topic is outside the scope of this work.

2.1.5 Refineries

Refineries present different types of challenges for their transition, as compared with other industries. The main fraction of the emissions occurs downstream of the refinery when the products are used, most notably when fuels are combusted in the transportation sector. The extraction of fossil fuels for use as feedstock is today central to the production processes in the refineries. However, with the eventual necessity to cease fossil fuel extraction to meet climate targets, the future direction of the refinery industry remains uncertain and could take several different pathways. The literature shows that refineries are highly heterogeneous in terms of their production portfolios, plant layouts, and complexity levels (see for example Biermann (2022) and references therein). Refineries commonly have multiple stacks spread over a large area, which makes it more complex to implement CCS. In this work, the refinery industry is limited to examining more-short-term intermediary solutions, where CCS and a switch of feedstock from fossil to biogenic are explored. Clearly, a complete transition from fossil-based to biogenic feedstock could represent a viable long-term solution, provided that substantial quantities of sustainably produced biogenic feedstock can be secured.

2.2 Non-technical barriers to the implementation of capital-intensive technologies

The CCS and H-DR technologies are examples of technologies that face several barriers to implementation. Various studies have identified the following key challenges: (i) regulatory barriers; (ii) market barriers; (iii) investment barriers; and (iv) infrastructure and coordination barriers (Barbhuiya et al., 2024; Chiappinelli et al., 2021; Löfgren & Rootzén, 2021; Watari et al., 2023). Regulatory barriers include uncertainties related to future carbon pricing, technology-specific regulation, and adjacent legislation, such as regulations. Market barriers

include uncertainties linked to the demands for carbon-neutral materials, and market entry barriers when more-expensive carbon-neutral materials have to compete with less-expensive carbon-intensive materials. Investment barriers relate to the capital-intensiveness of the technologies and the difficulties associated with acquiring private funding for technologies that are categorised as entailing high technological and market risks (Harring et al., 2021). Furthermore, governmental funding mechanisms are limited and are in many cases intended for First-of-a-Kind and flagship projects rather than large-scale implementation, such that few projects will secure these funds. Lastly, CCS and H-DR implementation is highly dependent upon the deployment of a support infrastructure, i.e., electricity grid, and a CO_2 transport and storage infrastructure. These key challenges link closely to the topics in the following sections: *Policy options for decarbonisation* (Section 2.3), *Demand for materials* (Section 2.4), and *Financing of capital-intensive technologies* (Section 2.5).

2.3 Policy options for decarbonisation

Assigning a price to carbon is a central component of climate policies designed to decrease emissions (Haites et al., 2023; Swedish House of Finance, 2024). Sector-based climate agreements, sectoral ETS or carbon tax regimes would divide the mitigation challenge up into pieces that are more manageable by focusing on actions within specific sectors with, for example, uniform products and/or production processes (see for example, Bradley et al. (2007) and Oberthür et al. (2021)). In the EU, the EU ETS is the most important policy instrument to regulate the emissions from heavy industries over time. However, although carbon pricing is a central part of climate policy, it is generally thought to be in itself insufficient to drive the transformative change that is needed (Bataille et al., 2023; Haites et al., 2023; Nilsson et al., 2021). Furthermore, the EU ETS is being reformed, by for example, phasing out the free allocation of emissions allowances to strengthen the carbon price signal. To avoid carbon leakage, a border-tax adjustment mechanism, the CBAM, is being phased in. Since border carbon adjustments would provide protection against carbon leakage, they would replace the free allowance allocation, which has the same purpose. However, the implementation of such adjustments entails numerous challenging regulatory choices, including its scope of applicability and the choice of methods for assessing the carbon content of products (Cosbey et al., 2019). The EUs border-tax adjustment mechanism, CBAM, which entered into its transitional phase in October 2023 (European Commission, 2023a), circumvents the assessment of carbon content as it is primarily targeting basic materials (as well as some semi-finished products and hydrogen).

It is observed that while the current policy regime that targets energy- and emissions-intensive industries has significantly improved in recent years, it remains unclear as to whether the current policy mix promotes long-term confidence and provides the incentives required for the investments in low-emissions technologies that must occur within the next few years if climate targets are to be met. Complementary policy measures are needed, several of which are described in the literature and briefly described below.

- Carbon contract for difference (Neuhoff et al., 2019; Richstein, 2017; Richstein & Neuhoff, 2022; Sartor & Bataille, 2019) is a subsidy agreement between the regulator and a firm, whereby the regulator commits to compensating the firm for the difference between the carbon price and a strike price, which ideally reflects the carbon price required to make a low-carbon production investment economically viable.
- The introduction, at the EU level (or as a national pilot), of a consumption charge that would be imposed on the consumption of carbon-intensive materials such as aluminium, steel or cement. A consumption charge would (i) ensure that the CO_2 cost associated with primary production is reflected also in the end-uses for which the material is destined; and (ii) create a revenue stream that could be used to finance support and incentive schemes aimed at accelerating the piloting and up-scaling of low-CO_2 production processes in the basic materials industries. The consumption charge could be based on tonnes of CO_2 or tonnes of material (Pollitt et al., 2020), depending on the aim of the charge.

Several possible support mechanisms and policy requirements that address cost and risk sharing have been proposed. These include:

- Governmental risk sharing and State funding during the early phases of the development and implementation of new technologies (Mazzucato & Rodrik, 2023), for example the reversed auctioning system for negative emissions operating in Sweden (Swedish Energy Agency, 2021), the EU Innovation Fund (European Commission, 2023d), and the US Inflation Reduction Act (Internal Revenue Service, 2022); the use of sustainable procurement requirements as a tool to create niche markets and to guarantee a market outlet (i.e., green lead markets (Agora Industry, 2024)) for low-carbon cement and steel (however, low-carbon materials must first be available on the market before they can be procured) (Åhman et al., 2023; Chegut et al., 2014; Kadefors et al., 2019; Simcoe & Toffel, 2014; Uppenberg et al., 2015);

innovative business models that create and capture value for the actors involved in the production, refinement, and use of materials, such as steel and cement (Chesbrough, 2010; Teece, 2010); and the issuance of Green Bonds, i.e., loans that are only approved for what are considered as “green projects” (Åhman et al., 2022; Chiappinelli et al., 2021; Monk & Perkins, 2020). To share more broadly the risks, there have been proposals to create: public-private partnerships as a climate finance policy with the function of de-risking and reducing the market uncertainties in relation to investments (Bhandary et al., 2021); trans-national decarbonisation clubs (Åhman et al., 2022; Hermwille et al., 2022); and co-operative arrangements, i.e., to deal with the technological risks related to co-ordination between actors (Harring et al., 2021). These measures can have more or less governmental involvement depending on their specific purposes.

2.4 Demand for materials

As mentioned above, meeting climate targets will generate significant demands for materials and services that have low or no climate impacts, driven partly by the need for resources to construct renewable power generation systems and similar technologies (Savvidou & Johnsson, 2023), as well as for building infrastructure and structures with low levels of embodied emissions (Karlsson et al., 2021; Liu et al., 2024). As a consequence of these events, the increased demand for low-emission materials will require the ramping up of production of carbon-neutral materials. However, producers are often reluctant to invest in low-emissions processes in the absence of a clear demand for such materials, since the low-carbon materials will compete against carbon-intensive materials on the market. At the same time, these carbon-neutral materials cannot be utilised until they are produced, which creates a 'chicken and egg' dilemma. To address this, strategies such as the green lead markets (Agora Industry, 2024), climate clubs (Hermwille, Lechtenböhmer, Åhman, van Asselt, et al., 2022), and green public procurement (Kadefors et al., 2019) can help to secure markets for carbon-neutral materials. Some companies are also engaging in joint ventures, whereby the materials are pre-sold on the market before production starts (e.g., Stegra[1], HYBRIT etc).

The future demands for materials, including carbon-neutral materials, are highly uncertain. Several studies have assumed a constant material demand over time, even in developed countries where the demand related to certain aspects of quality of life, such as buildings and

[1]Previously H2 Green Steel.

infrastructure, is expected to decline compared to developing countries. This is particularly the case in the EU-27 countries, which already have a well-developed infrastructure and a decreasing population. The trajectory of future material demands in the EU-27 countries remain uncertain, with the possibilities that they may increase, decrease, or remain stable (Marmier, 2023; Material Economics, 2019; Scrivener K., Habert G., De Wolf C., 2019). To reduce supply chain-related emissions, it is crucial to adopt strategies that promote the circular use of materials and enhance material use efficiency. Due to the uncertainties regarding future material demands, in this work, particularly in **Paper I**, a constant material demand for cement in the EU-27 is assumed through Year 2050.

2.5 Financing capital-intensive technologies

Apart from enabling policy instruments, the implementation of capital-intensive technologies, such as CCS and H-DR, requires substantial up-front capital investments. The capital costs associated with the implementation of transformative technologies are typically significant, and the costs related to proceeding from the pilot and demonstration scales (in the order of tens of millions of €) to the commercial scale (in the order of several hundreds of millions of €) carry a substantial risk for the investor. Technologies such as CCS and H-DR are often categorised as entailing high technological and market risks. These types of technologies are typically not eligible for conventional project financing, bank debt or venture capital investments (Ghosh & Nanda, 2010; Nemet et al., 2018; Polzin, 2017), making them particularly difficult to finance (Harring et al., 2021).

Apart from the private types of funding mechanisms, different governmental funding mechanisms exist, such as those available within the EU [e.g. the EU Innovation Fund, the EU's Just Transition Fund, the programme for Environment and Climate Action (LIFE), and the NextGenerationEU recovery plan]. However, most of these initiatives have a narrow focus in that they only fund demonstration, First-of-a-Kind, and flagship projects, or they are aimed at addressing inequalities between Member States. Thus, they are not designed to support the widespread up-scaling and deployment of low-emissions technologies. The difficulties associated with the incentivising and raising of the needed up-front capital to finance development and commercialisation are currently major barriers to the uptake of alternative, low-CO_2 technologies for applications in basic materials industries. Thus, this work proposes a novel alternative financing approach in addition to the instruments and mechanisms that are currently in place, so as to enable industries to be frontrunners in the transition to near-zero or net-zero emissions in the materials sector within the coming decades.

2.6 Contribution of this thesis

This thesis contributes with valuable insights into the important barriers and enablers for the implementation of capital-intensive technologies, i.e., CCS and H-DR. First, current regional (EU) and national (EU Member States) regulatory frameworks are explored with regards to how they facilitate or hinder the implementation of carbon capture technologies. Second, the costs incurred by basic commodity producers and end-product consumers for capital-intensive technologies are highlighted. Third, a novel financing approach is proposed to complement existing financial mechanisms, overcome market barriers, and assist industries in becoming frontrunners in the transition.

3 Methodology

The key methods applied to address the above-mentioned topics in relation to the transition of carbon-intensive industries are briefly described in the following sections. For more-detailed descriptions, the reader is directed to the respective papers. The following sections cover the methodologies used for both the product value chain and the technology-related value chain (for an overview, see Figure 2).

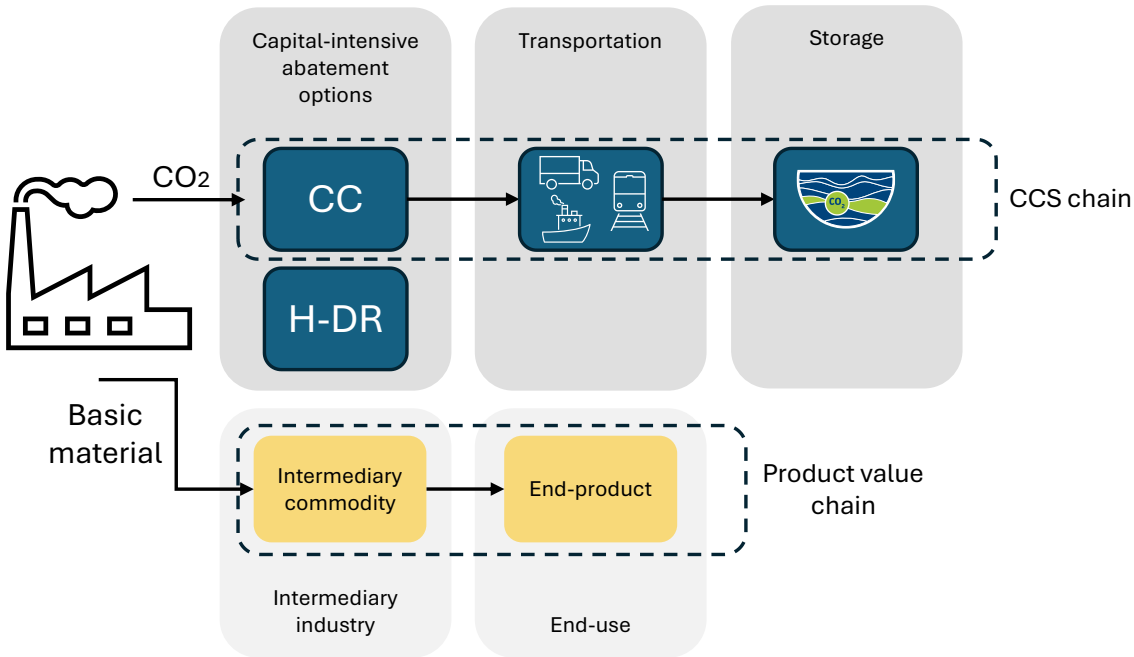

Figure 2. Schematic overview of the production system and related value chains (CCS value chain and product value chain). CC, Carbon capture.

3.1 Techno-economic assessment

Several of the analyses in the appended papers rely on techno-economic assessments to determine the production costs of low-emissions commodities. Thus, this section provides an overview. The production cost, C_s^m, of low-carbon materials, m, for each sector, s, is calculated according to Eq. (1):

$$C_s^m = CAPEX_s + OPEX_s^{var} + OPEX_s^{fix} \quad (1)$$

where $CAPEX_s$ is the annualised investment cost, based on a set discount rate and economic life-time, $OPEX_s^{var}$ is the variable operational expenditures, and $OPEX_s^{fix}$ is the fixed operational expenditures. The contents of the operational expenditures vary according to the specific industry and low-emissions technology evaluated (for additional details, please refer to the respective papers).

3.1.1 Value chains

The end-uses of commodities vary significantly, ranging from everyday single-use consumer products, such as disposable baby diapers, to more long-lived products, such as passenger vehicles and different infrastructure elements, such as roads and railways. The end-users associated with these end-uses also vary significantly, ranging from individual consumers to governmental agencies. This work analyses a wide range of commodity end-uses, to reflect the dynamics and impacts of end-users. A product value chain analysis can encompass many different things. In this work, product value chain analysis refers to an analysis of the cost propagation from the implementation of capital-intensive technologies (CCS and H-DR) through the value chain to the end-use. It is assumed that all production cost increases experienced by the basic commodity producers can be fully passed through the value chain to the end-product, thereby transferring the economic burden from the basic materials producer to the consumer so as to create a viable business case. This analysis is performed to showcase the impacts that the implementation of capital-intensive technologies could have on basic commodities and consumer prices (assuming that there is full cost pass-through and that no additional profit margins have been imposed by any actor along the value chain). Hereinafter, the cost increase for a low-carbon product, as compared to the cost of a carbon-intensive product, is referred to as the *relative cost increase*. See Figure 3 for a simple illustration of a value chain.

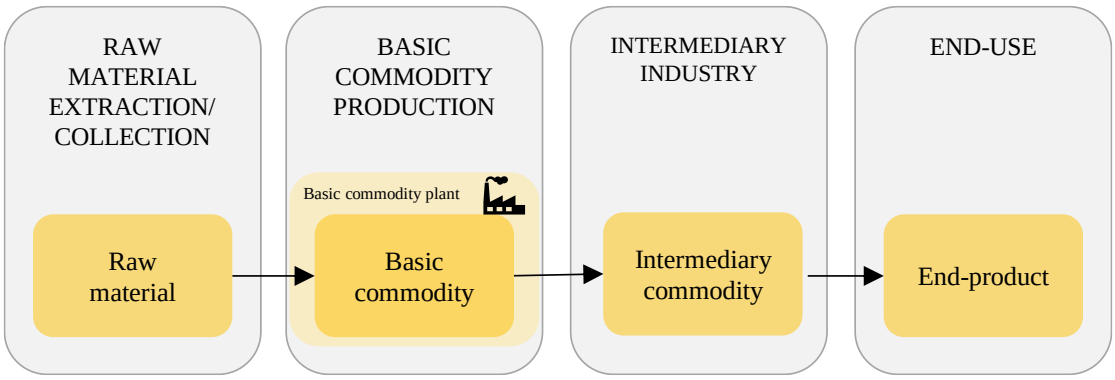

Figure 3. Illustration of a simple supply chain, proceeding from the collection/extraction of raw materials to the end-use for the basic commodity.

3.1.2 Transport of CO_2

Once the CO_2 has been captured, it must be transported to a designated storage site for permanent sequestration. In **Papers II** and **III**, since no detailed modelling of this step was conducted, a general cost for transporting and storing CO_2 (in the range of 35–55 €/CO_2) was assumed (Global CCS Institute, 2021). However, depending on the location of the plant and

the availability of inland transport infrastructure, the cost for transporting CO_2 will vary significantly between plants. Thus, in **Paper I**, this cost estimate is refined by including a more-detailed modelling approach for the transportation from plant to harbour, allowing for road, rail, and waterway inland transportation. The cost for storing CO_2 is determined by the storage providers, and early cost estimates show a storage cost of around 10 €/CO_2 (Zero Emissions Platform, 2010). However, to date, the storage offers received by actors have been far higher than 10 €/CO_2. Thus, in **Paper I**, the cost for storage is assumed to be as high as 60 €/CO_2 in Year 2020[2] and thereafter decreases linearly to 10 € per tonne CO_2 until Year 2050. For an overview of the transport and storage assumptions made in the appended papers, see Table 1.

Table 1. Overview of the cost assumptions for transport and storage of CO_2 made in the appended Papers.

	Paper I	**Paper II**	**Paper III**
Transporting CO_2 inland	Transport mode dependent (road, rail, barge)	-	-
Transporting CO_2 off-shore	0.021€/tonne-km	35–50 €/tCO_2	35–50 €/tCO_2
Storing CO_2	10–60 €/tCO_2 (linearly decreasing over time)		

3.2 Deployment of CCS technologies

The following sections describe the methodologies used in **Paper I** to assess the deployment of CCS technologies in the cement industries of the EU-27 countries.

3.2.1 Marginal abatement cost curves

Based on the techno-economic assessment, a Marginal Abatement Cost (MAC) curve is constructed to compare the costs of CCS deployment in the individual cement plants in the EU-27. The MAC is calculated for each plant and includes the following cost components: (i) capital and operational expenditures related to the capturing, conditioning and liquefaction of CO_2, assuming retrofit post-combustion CCS; (ii) inland and off-shore transportation from the cement plant to the storage location; (iii) storage of CO_2; and (iv) the costs for EU Allowances (EUA) for unabated emissions. The MAC curve is, in this work, not used in the traditional sense where the abatement cost is placed in increasing order; instead, the curve is constructed based on the year of CCS deployment according to the modelling.

3.2.2 Constructing decarbonisation pathways

The cost for CCS is determined annually for each plant. Each year, it is evaluated whether it is more cost-effective for a specific plant to invest in CCS, considering the full-chain costs, rather

[2]Representing the start year for the analysis, i.e., “current year”.

than continue to purchase EUAs for unabated emissions. This approach allows for the construction of decarbonisation pathways that illustrate how the EU-27 cement industry decarbonise over time through CCS implementation. This will later on be referred to as the *Baseline scenario*. Besides the purely techno-economic assessment of CCS deployment, aspects regarding the political landscape and its potential hindering or enabling effects on the transition are applied. These aspects include the application of national CCS-specific policies and EUA price development, and this will hereinafter be referred to as the *Alternative scenario*.

The national CCS-specific policies assessed include: cross-border co-operation for CO_2 transport; national operations programmes or plans in place to support research, demonstration and deployment of CCS; measures in place to support financially the development leading to the deployment of CCS; and further plans to support the appraisal of CO_2 storage sites, to prepare for the CO_2 transportation infrastructure or for the establishment of CO_2 hubs and clusters. A detailed overview of the EU Member States have implemented each of these measures is given in **Paper I**. Depending on the levels of deployment of these various CCS policies, cement plants within different Member States will exhibit varying abilities to invest in and implement CCS. For example, for an inland country, cross-border co-operation for CO_2 transport is essential for the implementation of CCS if no on-shore storage sites are available or planned.

3.3 Financing capital-intensive technologies

This section provides an overview of the theoretical framework and the methodology used to assess the Value Chain Transition Fund (VCTF) described in **Paper III**. The VCTF is a novel approach to financing the capital-intensive investments that are required to accelerate the industry transition towards zero-emissions practices, using CCS and H-DR as examples for the cement and steel industries. The VCTF is built upon three premises: (i) that the actors involved in emissions-intensive supply chains cannot achieve the goal of net-zero emissions on their own, but are instead mutually dependent for their transition; (ii) that most of the GHG emissions arise up-stream of the value chain, while most of the value is realised down-stream (Clift & Wright, 2000); and (iii) the notion that the implementation of deep mitigation measures (such as CCS and H-DR) exerts only a marginal effect on the overall cost for the end-consumer (Hörbe Emanuelsson & Johnsson, 2023; Rootzén & Johnsson, 2016, 2017).

The VCTF aims to: (i) share the financial risk related to the high, up-front investments required to transform key CO_2-intensive production processes in industry; (ii) create a bottom-up system

that is independent of governmental intervention and in which the industries become front-runners in the transition; (iii) internalise the value of low-carbon processes in the end-product; and (iv) create funding for projects that enable deep emissions cuts but that are associated with high technological and market risks. Figure 4 shows the general principles underlying the physical and monetary flows and the interactions amongst the actors involved in the supply chain actor formation and other enabling actors, such as banks and governmental bodies, when applying the VCTF.

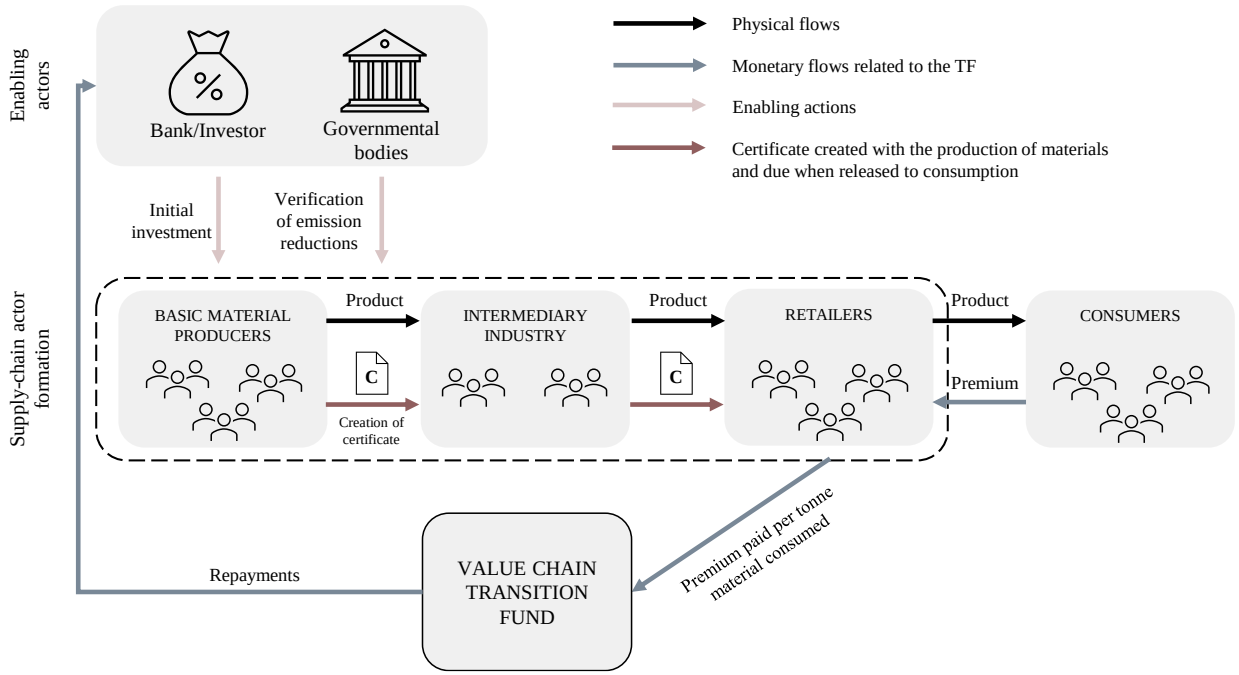

Figure 4. Principal flows and interactions between actors along the supply chain when the VCTF is applied.

The VCTF involves the following principal steps. A premium on low-carbon materials is paid by consumers. The premium is used to build the fund, with the objective of transforming the basic materials industry to a carbon-neutral system. The fund will be distributed in the form of amortising loans to support investments in transformative technologies. The level of the premium should be set by a supply chain actor formation that brings together many of the relevant stakeholders along the value chain of low-emissions materials. The premium could, for example, be set as the difference in production costs between carbon-intensive and low-carbon materials. With the issuance of certificates, market entry barriers can be overcome, thereby levelling the playing field between cheap carbon-intensive materials and low-carbon materials.

This work quantitatively assesses how the VCTF could finance the capital-intensive technologies needed to transform the European cement and steel industries to near-zero or net-zero emissions. This assessment includes: (i) assessment of the magnitudes of overnight investments (i.e., non-annualised investments including pure capital expenditures, without any additional costs or margins) that are required to implement transformative technologies in the cement and steel industries and the corresponding additional operational expenditures; and (ii) quantification of the time needed for the VCTF to meet these investment demands.

The overnight investments and additional operational expenditures are, in this work, evaluated by assessing the implementation of transformative technologies in various decarbonisation roadmaps and the estimations of specific capital and operational expenditures in the literature. Each roadmap includes a certain share of the transformative technology options needed under different scenarios that have different targets for CO_2 emissions reduction, and these are in focus in the present work (i.e., CCS and indirect electrification of the steel-making process using newly built H-DR technology, together with green hydrogen produced via electrolysis). It is important to note that while some roadmaps assess the net-zero industrial CO_2 emissions in Year 2050, other simply assess a 65% reduction in CO_2 emissions. The levels of deployment of CCS and H-DR in each roadmap are obviously dependent upon the CO_2 emissions reduction ambition and whichever other mitigation options are included (other than the transformative technologies). However, the costs for mitigation options other than CCS and H-DR have not been included in this work. This is because the focus is on transformative technologies with their high capital costs.

To assess the time-frame in which the VCTF could finance the demand for overnight investments in transformative technologies, the deployment level from the roadmaps is used together with an assumed premium level. The premium is, in this work, assumed to be the difference in production costs between the carbon-intensive and low-carbon materials, according to Eq. (2):

$$\text{Premium} = C_s^{m,\text{low emission}} - C_s^{m,\text{carbon intensive}} \qquad (2)$$

where $C_s^{m,\text{low emission}}$ is the production cost of the low-emissions technology and $C_s^{m,\text{carbon intensive}}$ is the production cost of the carbon-intensive technology option. The number

of years needed to recoup all the overnight investments plus additional operational expenditures is then calculated according to Eq. (3):

$$\text{Years} = \frac{\text{Total overnight investment cost+Additional operational expenditures}}{\text{Yearly VCTF premium revenue}} \quad (3)$$

Two different set-ups of the VCTF are explored, in which: (i) the overnight investment is covered by the VCTF; and (ii) both the overnight investment and additional operational expenditures for the first 5 years of operation are covered by the VCTF.

4 Selected Results

This chapter presents the results from the three appended papers to this thesis. The results presented in each subsection build on the methodologies described in the previous section. Selected results are shown for the three key overarching topics: (i) the deployment of CCS technologies in the cement industries of the EU-27 countries; (ii) the cost to consumers when implementing capital-intensive technologies (CCS and H-DR), using the cement, steel, pulp, WtE, and refinery sectors as examples; and (iii) the financing of capital-intensive technologies using CCS and H-DR in the cement and steel industries of the EU-27 countries as case studies.

4.1 Deployment of CCS technologies

The following sections, which are based on the work described in **Paper I**, explore the deployment of CCS in the EU cement industry in relation to the political landscape and available supporting infrastructure. Figure 5 shows the transition pathways for the EU-27 cement industry (see Section 3.2.2), with Figure 5a showing the *Baseline scenario* and Figure 5b showing the *Alternative scenario*. The *Baseline scenario* shows that under conditions of sufficiently high EUA prices and assuming sufficient CO_2 storage capacity, the cement industry decarbonises quickly and reach near-zero emissions already in Year 2035. However, the *Alternative scenario*, in which EUA prices are low and there are penalties for lacking national CCS-specific policies, shows that the cement industry will only reduce emissions by 70% by Year 2050 and 10% by Year 2030, as compared to Year 2020.

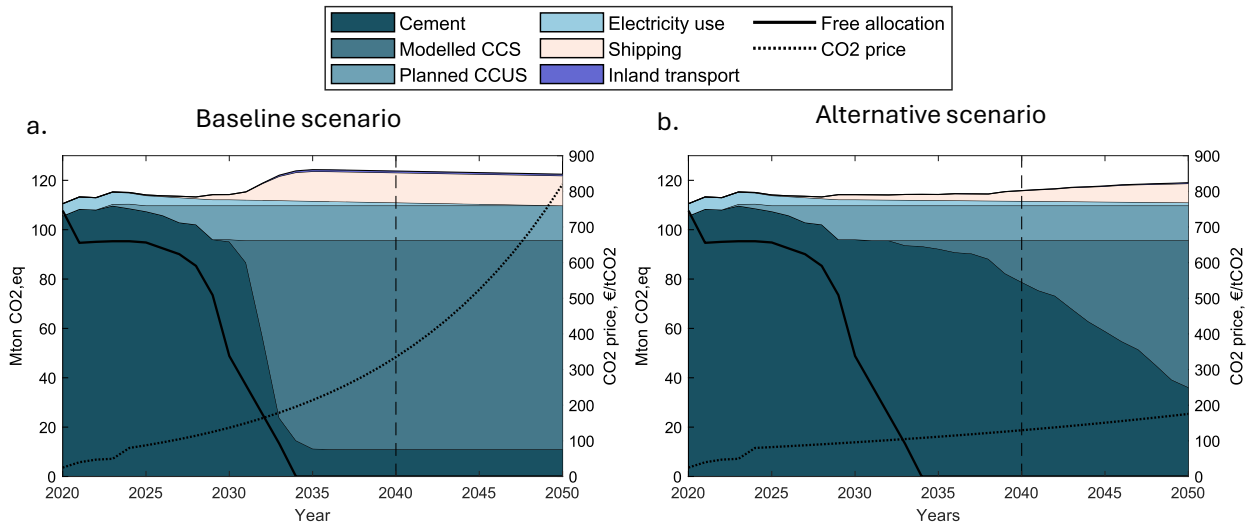

Figure 5. Transition pathways for the scenarios investigated in this work. a) *Baseline scenario*, b) *Alternative scenario* with combined low CO_2 price and a penalty for lacking national policies. The figure is based on results from **Paper I**.

Figure 6 shows the year of CCS deployment (on average) per region for the *Alternative scenario*. The figure shows those regions that might experience more difficulties in implementing CCS due to the plants being mainly located inland (implying long and expensive inland transportation) and/or lacking national CCS-specific policies. In general, CCS deployment occurs earlier in regions with plants that are located close to the shoreline, such that the need for inland transportation is limited. The results show that even for regions that have good conditions for inland transportation, the deployment of CCS can be drastically delayed due to policy landscape and supporting infrastructure factors. While the main contributor to the transition is the increasing EUA prices, this work demonstrates the importance of pro-active CCS policy incentives (especially for countries located inland without national CO_2 storage possibilities) to ensure the success and timeliness of large-scale CCS implementation in the EU cement industries.

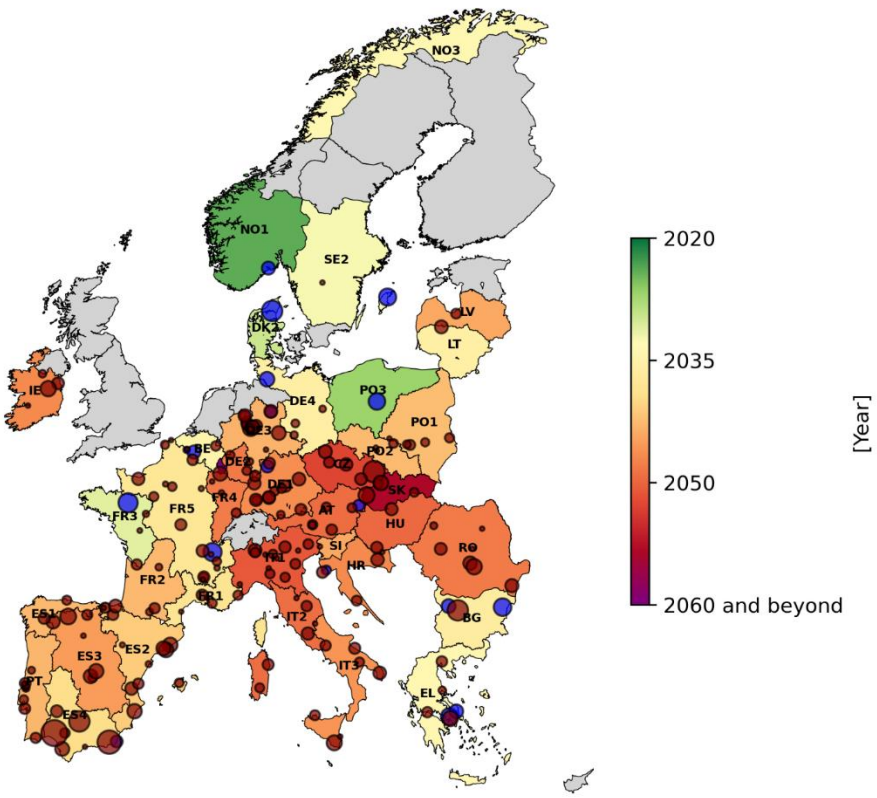

Figure 6. Map showing when in time the EU countries with cement plants implement CCS in the scenario with a low CO_2-price and time penalty for lacking CCS policies (colour scale to the right). The dots show the locations of the cement plants scaled to indicate their sizes in relation to their reported emissions levels in Year 2022, with modelled plants shown in red and announced plants shown in blue. Countries not included in the analysis, either due to not having any national cement plants or not being in the EU, are marked in grey. The figure presents results from **Paper I**.

4.1.1 Marginal abatement cost curves

Figure 7 shows the abatement costs of CCS implementation for each cement plant using Nth-of-a-Kind costs (see Section 3.2.1). The bars representing the abatement costs are ordered from left to right according to when in time each cement plant implements CCS according to the modelling results. Thus, the already announced projects, or potential early movers, are placed furthest to the left. As illustrated in Figure 7, the capture cost is higher the smaller the emissions source. Nonetheless, the figure reinforces the previous observation that inland transportation costs can be a significant barrier to CCS implementation, as they contribute substantially to high full-chain costs. Analysis of the potential early movers, i.e., those that have already announced CCS implementation, reveals that these projects do not necessarily represent the lowest full-chain cost (or even the lowest capture cost). This indicates that techno-economic factors are not the sole determinants of which plant implements CCS first.

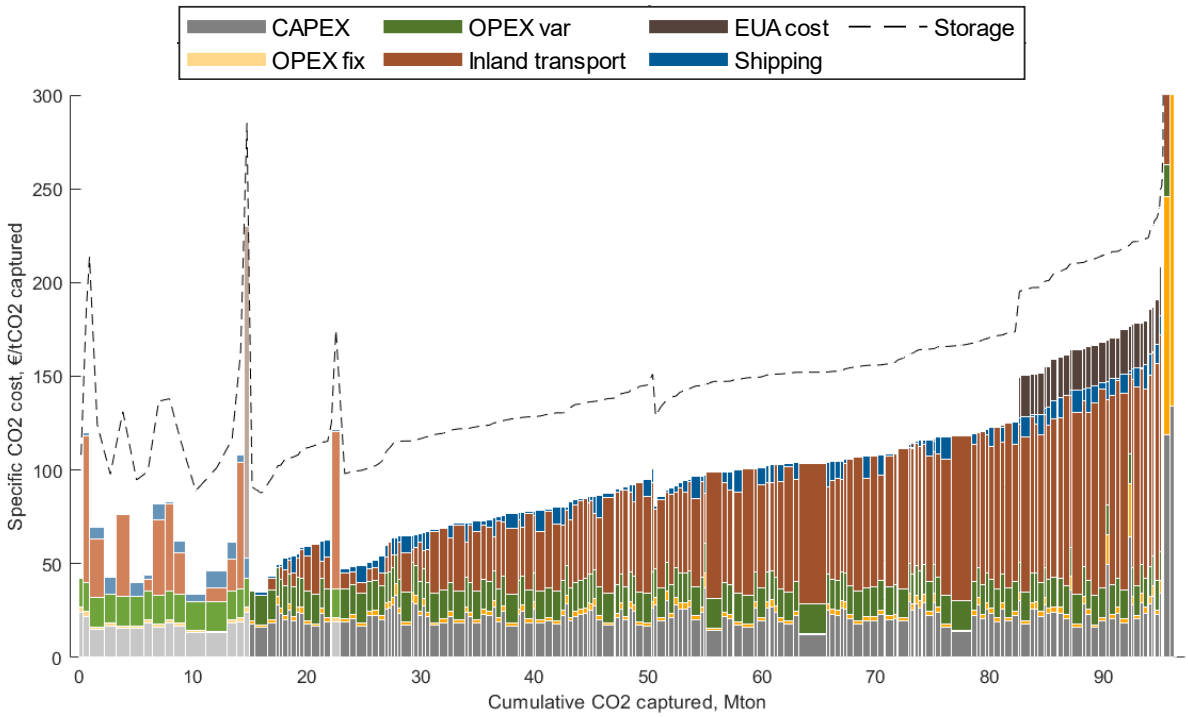

Figure 7. Marginal Abatement Costs based on the Nth-of-a-Kind cost for each cement plant in the EU, arranged in the order of earliest carbon capture implementation (from left to right) for the *Baseline scenario*. The width of each bar describes the plant's emission size, and the faded colours indicate the already announced plants. The *y*-axis is cut off at 300 €/CO_2-captured. The figure presents results from **Paper I**.

4.2 The cost to consumers of capital-intensive technologies

The results presented in the following section are derived from and build upon **Papers II** and **III** and relate to the cost to consumers when implementing CCS or H-DR in the basic

commodity industries. Figure 8 shows the relative cost increases and emissions reductions for the cement industry case study (cement to railway) (**Paper II**) (see Section 3.1.1). The production cost of the cement increases significantly (by 218%), although when moving further down the value chain to the end-use, the cost increment is small (1.2%). The life-cycle emissions associated with the cement itself are drastically reduced when implementing CCS (86%), which also significantly reduces the levels of emissions related to the railway (35%). Figure 8 also shows that the cost increase is already drastically reduced at the second actor in the supply chain, i.e., the concrete producer.

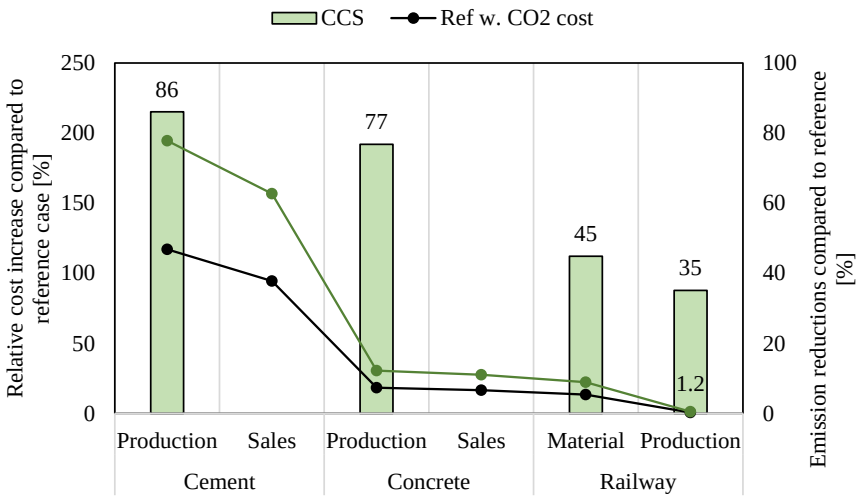

Figure 8. Relative cost increments (line graph) and emissions reductions (bar chart) along the value chain for the end-uses studied. 'Ref w. CO_2 cost' refers to the *Reference case* with an added carbon tax of 80 €/CO_2. The emissions reductions are calculated by comparing the emissions factors for CCS-produced commodities with that for the reference commodity. The figure presents results from **Paper II**.

Figure 9 shows the impacts on costs and emissions of the basic commodity and for the related end-uses for all industries and the related case studies included in this work (**Papers II** and **III**). The results show that, in similarity to the above-mentioned findings, when the costs of implementing transformative technologies (CCS or H-DR) are passed on down the value chain to the end-user, there is a small cost increase for a substantial reduction in the life-cycle emissions of the end-products and services. This is mainly 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. For most industries, the cost increase is drastically reduced already at the second actor along the value chain. As for the refineries, the situation is more complex. 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, see **Paper II**). Implementing CCS at the oil refinery without changing the feedstock will obviously have a

limited impact on life-cycle emissions reductions (a reduction of 3% in these cases, see **Paper II**). To achieve deep cuts in the life-cycle emissions of the fuel, the fossil feedstock used in the refinery must be replaced. The steel to passenger EV emissions reduction results presented in Figure 9 does not follow the same the rigorous LCA approach as used for the other product value chains. Instead, those calculations are more illustrative for comparative reasons.

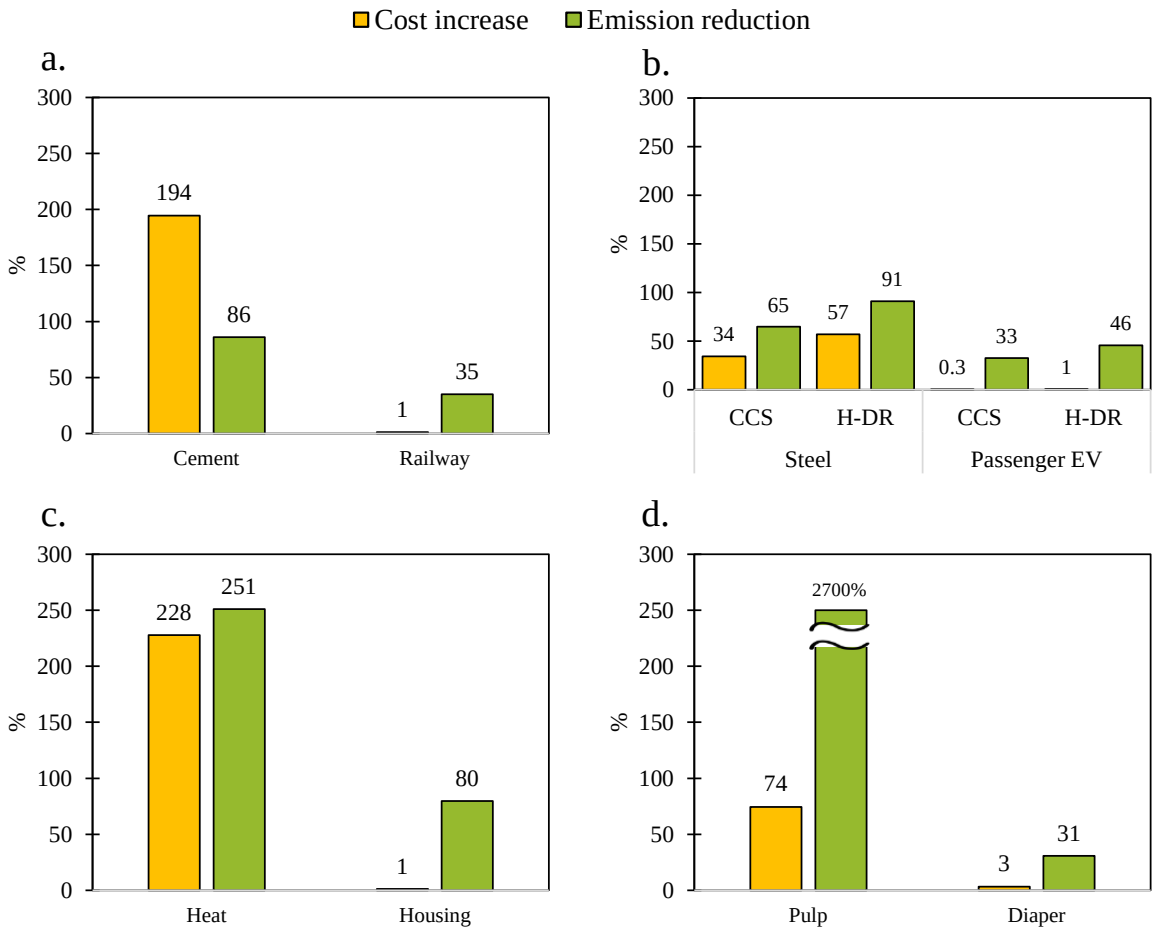

Figure 9. The impacts on cost increases and emissions reductions in the first and final steps of the value chains considered in this work. a) cement to railway, b) steel to passenger EV, c) heat to housing, and d) pulp to disposable baby diaper. The figure is based on results from **Papers II** and **III**. The emissions reductions for the steel refers to direct emissions reductions, and for the CCS case assumes an average value of total plant capture rate of 65%. The emissions reduction for H-DR are based on Wang et al. (2021) and assumes that 5% natural gas is injected into the furnace to keep the carbon content in the steel product.

4.3 Financing capital-intensive technologies

The following results, which are based on **Paper III,** explore the application of the VCTF to finance investments in CCS and H-DR in the EU cement and steel industries. Figure 10 shows the number of years that the VCTF needs to recoup all the overnight investments needed for CCS in the EU steel and cement sector. The bars in Figure 10 correspond to the average

estimations of overnight investment needs and operational expenditures, as presented earlier. The error bars show the maximum and minimum values in that range. Figure 10a shows that the VCTF can be used to recoup all overnight investment needs for CCS in the European cement sector within 4–6 years. When also including pay-outs for operational expenditures, this time-frame is extended to 7–8 years. Figure 10b shows the funds estimated to be needed for CCS in the steel industries can be recouped over a time-frame of <2 years (excluding the roadmaps that have excluded CCS as a decarbonisation option or where the technology is non-competitive). This period is extended to 5–6 years when operational expenditures are included. Similarly, around 3 years (range 2–10 years) are needed to recoup the overnight investments that have been estimated for H-DR, while this is extended to 16 years when including the operational expenditures.

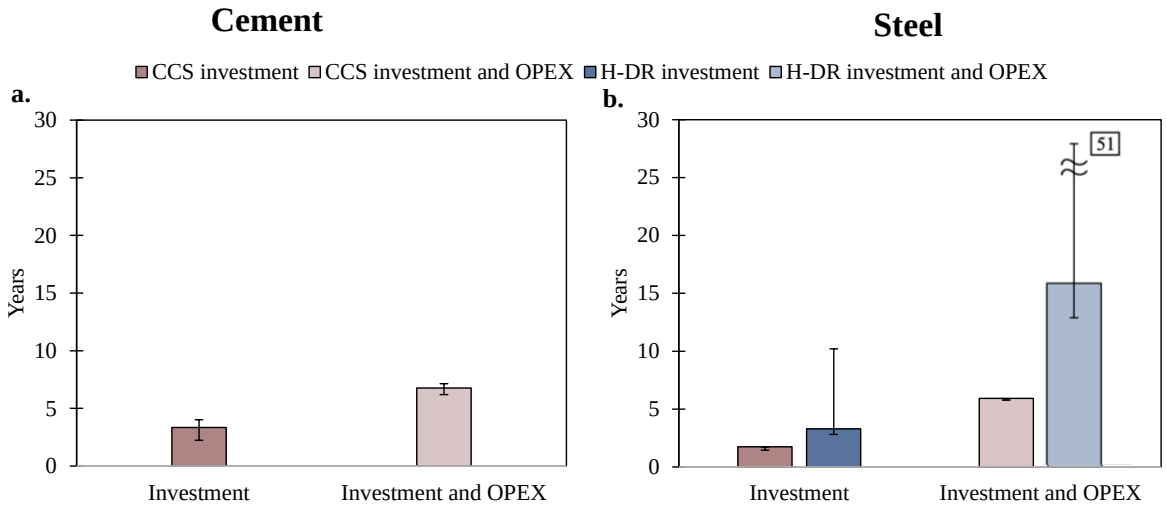

Figure 10. Numbers of years needed to finance the overnight investment needs and operational expenditures of CCS and H-DR for the European cement (panel a) and steel (panel b) industries, respectively, based on the previous assessment of the roadmaps. The figure presents results from **Paper III**.

However, the number of years required to recoup the costs in the H-DR case ranges from 12 to 51, with the maximum value being an extreme value that corresponds to the minimum total overnight investment cost and the minimum premium level. In this work, the premium level corresponds to the difference in costs between carbon-intensive and low-emissions production processes. Thus, the annual premium income is reduced in this scenario, resulting in a longer time being required to recoup the costs. In this case, the premium would realistically have to be increased to shorten the period required to recoup the costs. The opposite situation applies to the lower end of the range.

5 Discussion

The large-scale implementation of transformative technologies (i.e., CCS and H-DR) faces, as discussed in this work, investment barriers, market barriers, regulatory barriers, infrastructure and coordination barriers, and societal acceptance. This work explores some aspects of these barriers, and the following section discusses the implications of the results for these barriers.

Key carbon-intensive industries are hesitant to invest in the necessary capital-intensive technologies under the current policy landscape due to the risky nature of such substantial investments and the unpredictability of future policy developments. Market barriers arise as low-emission materials become far more expensive compared with the carbon-intensive alternative. This work shows that the production cost increases will be significant in several industries when implementing capital-intensive technologies, although, the cost-increment on end-products will be small (see Section 4.2). The marginal cost increase to consumers may be one enabling factor for societal acceptance of such technologies, especially because they simultaneously result in substantial emissions reductions (see Figures 8 and 9). Studies show that consumers prefer to purchase products from firms that are engaged in carbon emissions reduction activities (Abdallah et al., 2010), and there is a significant public willingness to pay for climate change mitigation (Alberini et al., 2018).

The principle that transformative technologies impose only a marginal cost increase on end-products enables the concept of VCTF (Section 3.1 and 4.2). The VCTF could be used to overcome market barriers and address investment barriers by recouping the costs of the investments and operational expenditures needed for transformative technologies, i.e., serving as a risk sharing mechanism between the actors along the supply chain. Thus, the results presented in this work demonstrate how a VCTF can be used to move the financial risk linked to the high up-front investments from the basic material producers, so as to enable the investments required to transform key CO_2-intensive production processes in industry. In addition, the VCTF is designed to create a bottom-up system in which basic material producers can be frontrunners in the transition without governmental involvement. Thus, the VCTF would enable industry to be frontrunners in the transition to near-zero or net-zero emissions in the materials sector within the coming decades, while hedging against political uncertainties. The VCTF could be especially useful in accelerating the transition in nations and regions that currently have insufficient climate policies to drive the transition. Yet, it is important that the increased costs related to investments in transformative technologies can be transferred to the

end-consumer in a transparent way, so that a limited impact on the price of the final product can be demonstrated and communicated to the end-consumer in a credible way. Thus, communication with consumers must be transparent and engage the public in a way that creates markets for low-carbon products. It will also be important for emissions reductions to be verified by third-party actors, to assure consumers of full credibility and transparency.

The early movers in the cement industry indicates a willingness to accelerate the transition to more-sustainable practices, even beyond the constraints of the current policy framework (see Section 4.1). Our analysis of consumer costs demonstrates that by the second stage of the value chain (e.g., concrete producers in the cement case study), the impact on the intermediary product cost is considerably reduced compared to the initial stage (e.g., cement producers) (see Figure 8). This suggests that intermediate industry actors will play a crucial role in facilitating the transition, as they face lower cost increases compared to the basic material producers. Given that cement producers are already taking steps toward CCS implementation, as evidenced by the early movers, producers of concrete could further drive the demand for low-emissions cement.

Although the VCTF would enable industries to be frontrunners in the transition, this work also illustrates the importance of increasing EUA prices for CCS implementation (see Section 4.1). However, the development of the EUA price over time is uncertain, especially when factoring in political uncertainties. This work also demonstrates the importance of pro-active CCS-specific policy incentives (especially for countries that are located inland without national storage possibilities), as well as strong awareness of CCS cost unknowns, in order to succeed with large-scale CCS implementation. Our findings suggest that cement plants that are situated in proximity to ports or in areas with a well-developed infrastructure for cost-effective inland CO_2 transportation are more likely to transition to CCS technologies at an earlier stage than those in less-advantageous locations. Conversely, the results indicate that even if regions meet these requirements, the transition to CCS may be delayed in the absence of pro-active, CCS-specific regulatory measures. This underscores the necessity of implementing not only supply-side measures but also demand-side strategies to ensure a timely transition. The *Alternative scenario* in Section 4.1 illustrates that the emissions reductions could be as low as 10% in Year 2030 and 70% in Year 2050, as compared with Year 2020. This is not in line with the current EU ambitions to reduce emissions by 55% by Year 2030 (compared to Year 1990) and to be climate-neutral by Year 2050. Obviously, emissions reductions could occur more rapidly in other sectors to reach the intermediate goal in Year 2030. However, to reach climate neutrality

by Year 2050, all sectors in the economy must deeply decarbonise. It is important to note that the EU climate ambition of climate neutrality also allows for CDR, even though that is not allowed within the EU ETS.

Another important factor for the transition that has not been included in this work is societal acceptance of capital-intensive technologies, and especially CCS, since this technology has been historically widely debated. CCS is a debated topic for several reasons, including the risks of CO_2 leakage during transportation and storage, and the history of economically unsuccessful projects that have largely been funded by Society. Furthermore, the implementation of CCS has been largely lobbied for and promoted by oil and gas companies, as it could allow for the continued extraction and use of fossil fuels, upon which the current economic system is heavily reliant. Clearly, production-related emissions could be eliminated if production were to cease entirely, although it seems unlikely that Society will completely overhaul the current economic system and discontinue the use of bulk materials such as cement and steel. However, there is a great need for demand-side measures, behavioural changes, and sufficiency measures to ensure the success of the transition to near-zero emissions practices.

6 Conclusions

A broad portfolio of supply- and demand-side mitigation measures will be needed to comply with EU climate targets. The successful and timely roll-out of transformative technologies (i.e., CCS and H-DR) will be needed up to Year 2050, although there are significant challenges linked to their implementation. These challenges include investment, market, regulatory, infrastructure, and coordination barriers. This work explores the conditions for the implementation of transformative technologies as a mitigation measure for deep decarbonisation in the emission-intensive industries.

This work emphasises the significance of increasing EUA prices to make low-emission technologies competitive. Even though the EU ETS is an important policy instrument in this context, this work shows that exclusive reliance on carbon pricing will not ensure a successful and timely transition. Instead, this work shows that other CCS-specific regulation are crucial for the deployment of CCS technologies, and that the deployment of supporting infrastructure cannot be taken for granted. Plants located inland will face additional difficulties regarding their CCS implementation due them having higher full-chain carbon capture costs. This work shows that there is currently sufficient announced CO_2 storage capacity to ensure the cement industry transition, although competition may arise between sectors.

It is often argued that policy instruments are needed to level the playing field between low-carbon and carbon-intensive materials and commodities. This work shows that this is true upstream of the value chain for basic material producers, for whom the costs of implementing low-emission technologies (such as CCS and H-DR) will be significant (35-230%). However, when the costs for implementing low-emission technologies are distributed along the product value chain to the end-product where the material is actually being used, the cost increment is small (1-3%).

The above-mentioned enabling principle can be utilised to address the investment and market barriers, through a novel financing approach, the Value Chain Transition Fund (VCTF). The VCTF is a complementary financing mechanism that allows for industry to act independently of governmental intervention. The VCTF could be used to finance investments in CCS and H-DR in the cement and steel industries in 2–6 years. The VCTF could also overcome market barriers and level the playing field for low-emission materials in a market where they compete against carbon-intensive materials.

Taken together, the results from this work highlight the barriers and possible enablers associated with deploying capital-intensive technologies. Given that the hurdles are many, to succeed with the transition we cannot rely on carbon pricing to be the silver bullet, instead we need a portfolio of complementary policy measures and financing mechanisms. To quote Bataille et al. (2024): “there is no one-size-fits-all policy instrument”, and we need to have “an attitude of experimentation” since failures will surely occur.

7 Future work

The topic of decarbonisation of carbon-intensive industries is a broad one, with numerous important issues to be explored. Future work should be aimed at providing a more-comprehensive understanding of the industry's transition. This work has focused mainly on the barriers to the implementation of key capital-intensive technologies. However, less attention has been given to the drivers of the transition and the roles of the different actors in the value chain.

It is often argued that policy will be the most-important tool to achieve industrial decarbonisation. However, Li & Strachan (2019) have shown that the power sector, residential heating, and the passenger road transport sector transition can achieve similar decarbonisation levels regardless of whether government-led or Society-led, as long as both entities are eventually involved. As shown in the present work, industry does not rely solely on policy instruments and financial incentives to transition, and the potential of intermediary producers to act as enablers during the transition is also demonstrated.

This situation should be explored further for the industrial transition, with the aim of focusing on expanding the roles of the actors along the supply chain towards enabling the transition to near-zero or net-zero emissions. The considered actors range from basic material producers to intermediary industry, to manufacturers, and consumers. Identifying the actor groups that have the power to drive the transition and assessing whether they can influence the speed and timing of the transition will be of particular interest. In addition, the potential for certain groups to take on a leading role in the transition will also be explored.

Further investigations are needed into how policies — both production-oriented (directed toward producers) and consumption-oriented (directed toward consumers) — will impact the transition. It remains to be determined whether a top-down policy push will be the most-important driver of the transition, or if instead a bottom-up consumer or industry pull will emerge as the frontrunner and enabler.

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