THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Unlocking industrial decarbonisation: investment risk, policy uncertainty, and value chain opportunities

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Abstract

The deployment of capital-intensive technologies, such as Carbon Capture and Storage (CCS) in the cement industry and for hydrogen-based direct reduction of iron (H-DRI) in the steel industry, presents a unique challenge for industrial decarbonisation. These technologies require substantial up-front investments, while their site-specific nature limits learning effects and cost reductions. The large-scale deployment of decarbonisation technologies also relies on co-ordination across multiple actors to ensure the availability of an enabling infrastructure, which includes electricity grids (for H-DRI) and CO_2 transport and storage networks (for CCS). As a result, production costs increase relative to conventional emissions-intensive processes.

The European Union Emissions Trading System (EU ETS) plays a central role in addressing the cost gap between low-emissions production and conventional production. However, uncertainty regarding the future development of allowance prices limits the effectiveness of the EU ETS as a stand-alone driver of investment. While low-emissions materials are significantly more expensive at the production stage, this thesis shows that cost increases are considerably diminished when passed down-stream along the value chain, resulting in relatively modest impacts on the end-users. Thus, adopting a value chain perspective provides a more-comprehensive understanding of the implications of industrial decarbonisation, while demonstrating that deep emissions reductions can be achieved with comparatively small increases in the costs of the end-products.

Despite this, current policy incentives are insufficient to trigger large-scale investments, and in addition this work shows that the required investment volumes for transitioning the EU cement and steel industries to near-zero emissions over the next 25 years far exceed historical levels in the EU. This thesis shows how co-ordination of actors along the value chains provides an opportunity in sharing the costs and risks associated with transformative technologies. It proposes a Value Chain Transition Fund (VCTF), which will leverage down-stream cost pass-through to help finance capital-intensive investments and overcome market barriers. The analysis shows that the imposition of small premiums on end-products could enable the recovery of CCS and H-DRI investments within a few years.

Finally, this thesis shows that differences in firms' willingness to make investment decisions under conditions of uncertainty play an important role in shaping the pace of industrial decarbonisation. While predictable policy frameworks are essential, investment decisions depend on the risk tolerance levels of companies, with frontrunners investing under uncertainty and others delaying until stronger incentives emerge. In addition, consumer willingness to pay for low-emissions materials acts as a complementary "pull" mechanism, accelerating adoption, particularly among risk-averse firms, and reinforcing the effect of long-term contracts. Overall, combining policy "push" with demand-side "pull" mechanisms is significantly more effective than solely relying in either of these.

Keywords: Industry, Decarbonisation, Materials, Capital-intensive technologies, CCS, H-DRI, Value chains, Value Chain Transition Fund, Producers, Consumers, Policy.

List of publications

This thesis is based on the following papers, which are referred to in the thesis by their Roman numerals:

I. Hörbe Emanuelsson, A., Johnsson, F. The Cost to Consumers of Carbon Capture and Storage — A Product Value Chain Analysis, *Energies,* **2023**, *16*, 7113.

II. 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, *Energy Policy*, **2025**, *196*, 114413.

III. Hörbe Emanuelsson, A., Rootzén, J., Johnsson, F. Deployment of carbon capture and storage in the cement industry – Is the European Union up to shape?, *International Journal of Greenhouse Gas Control*, **2025**, *146*, 104442.

IV. Hörbe Emanuelsson, A., Beiron, J., Johnsson, F. From demand to decarbonisation: The roles of industry, consumers, and policy-makers in the transition of materials production systems. *Submitted for publication.* **2026**.

V. Hörbe Emanuelsson, A., Rootzén, J., Johnsson, F. Investment perspectives of the feasibility of the basic materials transition to net-zero emissions in the European Union. *Submitted for publication.* **2026**.

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

Other publications not included in the thesis:

- Lehtveer, M., Emanuelsson, A. BECCS and DACCS as negative emission providers in an intermittent electricity system: why levelized cost of carbon may be a misleading measure for policy decisions. Frontiers in Climate, **2021**, *3*:647276.

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CHAPTER 1

Introduction

Ensuring future supplies of basic materials, such as cement and steel, while meeting climate targets will require deep decarbonisation of these industrial processes (IPCC, 2022). Achieving near-zero emissions in these sectors relies on the widespread deployment of a portfolio of mitigation measures, including large-scale electrification, Carbon Capture and Storage (CCS), fuel and feedstock switching, and circularity strategies (Rissman et al., 2020). These measures reduce both production-related emissions and the need for primary material production. In the cement and steel industries specifically, near-zero emissions rely on the deployment of CCS and hydrogen direct reduction of iron (H-DRI) coupled with an electric arc furnace (EAF).

CCS and H-DRI are often categorised as 'lumpy' technologies, meaning technologies that require large-scale capital-intensive investments and provide limited opportunities for learning (Choi & Jae, 2023). Capital-intensive investments in low-emissions production technologies result in two inter-related challenges: ensuring their profitability; and securing financing to make the initial investment. The increased capital and operational expenditures result in more-expensive materials, creating a cost gap between low-emissions materials and their carbon-intensive counterparts. Which means that at present, low-emissions materials face a cost disadvantage when competing with cheaper emissions-intensive alternatives in existing markets. In addition, transitioning from pilot and demonstration projects to full commercial scale requires investments that often amount to several hundreds of millions of euros, making it challenging to finance these technologies through conventional channels such as commercial bank loans, project finance or venture capital. As a result, securing the necessary upfront capital remains a major obstacle to the deployment of low-emissions mitigation technologies in heavy industry, and the deployment of such mitigation measures presents a unique challenge.

Beyond the higher costs associated with low-emissions technologies, several additional barriers complicate their large-scale deployment, such as problems associated with co-ordinated investments in enabling infrastructure, which includes electricity grids, hydrogen supply chains, and CO_2 transport and storage systems. This need for co-ordination across multiple actors, together with the need to adapt technology-specific regulations for the deployment of CCS and H-DRI, adds further uncertainty to investment decisions and slows the large-scale deployment of capital-intensive decarbonisation technologies.

The European Union (EU) seeks to address these challenges through policy interventions. To reduce the cost gap between conventionally produced materials and low-emissions materials, the most-important policy instrument is the EU Emissions Trading System (EU ETS). The EU ETS is a cap-and-trade system in which the total emissions cap declines over time, placing upward pressure on the price of emission allowances, thereby increasing the cost of carbon-intensive materials. The price of emissions allowances increased significantly in the early 2020's (from around 4 €/tCO_2 in Year 2013 to around 80 €/tCO_2 in Year 2023) (EEX, n.d.). During the same period, the momentum towards industrial decarbonisation efforts increased significantly, with a growing number of companies announcing initiatives and investments aimed at transitioning to low-emissions production. Automotive manufacturers, such as Volvo Cars and Polestar, signalled strong demand for low-emissions materials, while major industrial actors initiated large-scale transformation projects, including fossil-free steel initiatives such as HYBRIT and Stegra in Sweden and Thyssenkrupp Steel's tkH2Steel project in Germany. In the cement sector, companies such as Heidelberg Materials and Holcim also pursue CCS as a pathway to low-emissions production.

Despite this momentum, significant uncertainty remains regarding the future development and timing of the pricing on emissions allowances within the EU ETS. This uncertainty has been amplified by geopolitical instabilities, as well as increasing political pressure from some EU Member States and industries to ease the stringency of the ETS due to increasing energy prices. In March 2026, 10 EU Member States called for the weakening, or even suspension, of the EU ETS (Euro News, 2026; Reuters, 2026). Such developments create uncertainty around the policy landscape and the profitability of low-emissions investments, thereby weakening the incentives for industrial actors to make such investments. As a result, the momentum towards industrial decarbonisation has slowed in several cases, with a number of planned transition projects being paused, delayed or even cancelled.

While policy plays a major role in enabling the transition, industrial actors and consumers also have important parts to play in the transition. Industrial actors (i.e., material producers) express varying degrees of willingness to invest under conditions of uncertainty. Some actors are not willing to accept the risk of such an investment (i.e., risk-averse actors), preferring to wait until the policy environment provides stronger incentives that reassure that the investment will be profitable. Other actors would prefer to move first (i.e., non-risk-averse) and be front-runners in the transition, thus making them more willing to invest under conditions of uncertainty. Furthermore, consumers' willingness to pay for low-emissions products can contribute to closing the cost gap and hedging the investment risk between conventional materials and low-emissions cement (Hörbe Emanuelsson et al., 2025). By increasing the demand for low-emissions materials, products or services, consumers can exert a pulling effect on the market, complementing policy efforts and encouraging industry to accelerate the transition towards low-emissions production. However, the timing and magnitude of the demand for low-emissions materials, as well as consumers' willingness to pay for such materials, are unknown.

1.1 Research space

This thesis focuses on industrial decarbonisation, and this sub-section aims to position its contribution within the broader body of the literature. The field of industrial decarbonisation is extensive and encompasses a wide range of perspectives and methodological approaches. The various strands of the literature collectively contribute to understanding and enabling the transition of industry towards near-zero emissions by mid-century. However, the studies in the literature differ significantly in the ways in which they represent industrial systems, model the transition, and capture decision-making processes, as well as in terms of spatial and temporal scopes. The literature is presented here using six central themes: 1) The cost of mitigation options; 2) value chain implications; 3) transition modelling; 4) green industrial policy; 5) transition under uncertainty; and 6) feasibility of the transition. While the field of industrial decarbonisation is broader than the above-mentioned topics, these are the ones that are most relevant to this work. Table 1 gives an overview and examples from the literature in the field of industrial decarbonisation, and each topic is explained briefly below.

The cost of mitigation options is often analysed from the perspective of a single "average" plant in a given year, resulting in a static representation of costs. Typically, this strand of the literature addresses how much more expensive low-emissions materials become when CCS and H-DRI technologies are implemented (see, for example IEAGHG (2013)). Other studies include a broader temporal scope to analyse how costs develop over time and under different conditions (sees for example Vogl et al. (2018)). While this perspective is important for understanding the implications for plant owners and potential market barriers, it neglects the value chain perspective and the broader context of how and where these materials are used. This perspective is further addressed in this thesis (see the next theme of *Value chain implications*).

The literature on *Value chain implications* takes a broader perspective regarding the deployment of mitigation options and includes the full product value chain, from material production to end-use. It analyses the impacts on end-products and consumers when implementing capital-intensive mitigation options at the basic materials production plant. Typically, the increase in costs and the associated impacts on emissions linked to basic materials and end-products are analysed (see, for example Rootzén & Johnsson (2016a), Rootzén & Johnsson (2016b), Subraveti et al. (2023), and Klement et al. (2021)). This work builds on this approach by extending the analysis to a broader range of sectors and end-products.

Transition modelling of industrial decarbonisation typically adopts a dynamic perspective, capturing how the transition unfolds over time. Different modelling approaches are used, including optimisation and simulation models (see for example Neuwirth et al. (2024a), Neuwirth et al. (2024b), and Yang et al. (2023)). These models also differ with regards to their starting points, with some based on the existing system (brownfield) and others assuming a greenfield configuration. Likewise, the objectives of the modelling vary, with some studies identifying the least-cost transition pathways through optimisation, while others explore transition outcomes under uncertain future developments. This work takes a simulation approach to analyse further the transition outcomes under uncertain future policy developments, industry risk behaviours, and consumer demand and willingness to pay for low-emissions materials.

The theme of G*reen industrial policy* includes analyses of the development and impacts of existing policy instruments, such as the EU ETS, as well as assessments of novel enabling policies and the remaining gaps that must be addressed to enable the deployment of capital-intensive technologies (see, for example Richstein & Neuhoff (2022), Pollitt et al. (2020), Chiappinelli et al. (2021), and Bataille et al. (2024)). While this work does not analyse policy in detail, it relies on the EU ETS as a key element in the modelling and analysis of industrial transition pathways.

The literature on the *Transition under uncertainty* theme reflects the multiple sources of unpredictability that influence industrial decarbonisation pathways. These include uncertainties related to future policy developments, such as the timing, stringency, and stability of regulatory frameworks. Uncertainty also extends to actor behaviours, including how industrial firms respond to policy signals and their willingness to adopt low-emissions technologies (see, for example Yang et al. (2023)), as well as uncertainty in relation to demand, and consumer behaviours (see for example Li & Strachan (2019)). These uncertainties are included in this work when modelling industrial transition pathways, allowing for a more-comprehensive representation of transition dynamics.

The *Feasibility of the transition* theme is analysed from multiple perspectives in the literature, particularly with regard to the development and large-scale deployment of emerging technologies. Technological development is commonly conceptualised as an S-curve that consists of four phases: formative, acceleration, stable growth, and saturation. Within this strand of the literature, attention is also given to the high failure rates of early-stage projects, highlighting the fact that announced investments do not necessarily translate into realised capacity. As a result, these studies critically assess whether low-emissions technologies can be deployed at a pace that is consistent with climate targets, given the historically observed patterns of technological diffusion (see, for example Kazlou et al. (2025)). Beyond the technologies themselves, feasibility is further shaped by the availability and expansion of supporting infrastructure. This includes, for example, the infrastructure for CO_2 transport and storage, as well as electricity generation and grid capacity. The literature emphasises that the transition depends not only on the scalability of individual mitigation options, but also on the co-ordinated development of inter-connected systems (see, for example Watari et al. (2023)). While this work does not account for technology growth patterns, it contributes to this strand of the literature by explicitly analysing transition feasibility from the financing perspective, which is an aspect that has not often been considered in previous studies.

Given the topics outlined above, this work broadly focuses on industrial decarbonisation, with specific emphasis on the deployment of capital-intensive technologies. The deployment of these technologies is analysed from a transition pathway perspective under uncertain policy and regulatory developments. In addition, the work examines the value chain implications of deploying capital-intensive technologies. The transition is further analysed from an actor-based uncertainty perspective, in particular focusing on how the industry's willingness to invest in capital-intensive technologies is shaped by uncertain policy developments, as well as the uncertainties linked to consumer demand and the willingness to pay for low-emissions materials.

Table 1. Overview of the research space and examples of key studies in the literature on industrial decarbonisation.

Research topic	Key focus	Typical methods	Spatial scope	Temporal scope	Example references
The cost of mitigation options	Technology costs of mitigation options and performance	Process modelling Techno-economic assessments	Plant-level	Single or multi-year	Vogl et al. (2018) IEAGHG (2013)
Value chain implications	Value chain impacts on costs and emissions from the deployment of decarbonisation options	Product value chain analysis Life Cycle Assessment	Plant-level	Single year	Subraveti et al. (2023) Klement et al. (2021) Rootzén & Johnsson (2016a) Rootzén & Johnsson (2016b) Skelton & Allwood (2013)
Transition modelling	Deployment of decarbonisation options over time and decarbonisation pathways	Optimisation Simulation Agent-based modeling	Regional	Multi-year	Neuwirth et al. (2024a) Neuwirth et al. (2024b) Yang et al. (2023)
Green industrial policy	Existing and novel policies to enable the transition in the short-term and long-term	Policy analysis	Country-level / Regional	Multi-year	Bataille et al. (2024) Richstein & Neuhoff (2022) Chiappinelli et al. (2021) Nilsson et al. (2021) Pollitt et al. (2020)
Transition under uncertainty	Uncertainty related to the development of the policy landscape, and actor behaviour	Varies	Varies	Multi-year	Stenström et al. (2025) Yang et al. (2023) Li & Strachan (2019)
Feasibility of the transition	Technology development (growth patterns of new technology) Feasibility of deploying supporting infrastructure	Varies	Varies	Multi-year	Kazlou et al. (2025) Watari et al. (2023)

1.2 Aim of the work

The overall aim of this thesis is to analyse the challenges and explore the opportunities to deploy capital-intensive mitigation technologies in the EU's basic material industries, here represented by the deployment of CCS in the cement industry and H-DRI in the steel industry, in order to meet climate targets in a timely manner. This work evaluates the key techno-economic, financial, market, policy, and actor-interaction factors that shape the deployment of capital-intensive technologies required for deep decarbonisation.

Specifically, the thesis addresses the following topics:

- **Cost**. Evaluations of the impacts of capital-intensive technologies on the production costs of basic materials, and the resulting cost gap between low-emissions and conventional emissions-intensive alternatives. In addition, a value chain perspective is adopted to analyse how these costs propagate to the end-products in which the materials are used, alongside the associated emissions reductions.
- **Financing**. Assessments of the financing required for the deployment of capital-intensive technologies in the EU cement and steel industries to achieve near-zero emissions; the funding available through EU mechanisms; the role of novel financing instruments; and past investment patterns in capital-intensive technologies in heavy industries.
- **Uncertainty**. Analysis of the uncertainties that are crucial for the deployment of capital-intensive technologies, such as climate policy and regulatory developments, industry risk tolerance, and consumer demand and willingness to pay for low-emissions materials.

1.3 Outline of the thesis

The thesis consists of this summarising essay and the five appended papers. Following this introductory chapter, Chapter 2 provides some background of the key aspects for this thesis, and Chapter 3 describes the key methodologies used when carrying out the work. Chapters 4, 5, and 6 describe the key results and discussions from the appended papers. Chapter 4 presents the cost and emissions analyses throughout the value chain when implementing low-emissions technologies. Chapter 5 presents the perspective of the financing of capital-intensive technologies, and Chapter 6 presents and considers the uncertainties related to the key parameters for the transition, such as policy developments, industry risk tolerance, and consumer demand and willingness to pay for low-emissions materials. Chapter 7 concludes the thesis with an overall summary of the key outcomes and proposals for future work. While the five appended papers analyse six different industries, namely cement, steel, refineries, petrochemicals, pulp, and Waste-to-Energy, this thesis focuses on the cement and steel industries.

The focus of each of the appended papers is briefly described below.

Paper I analyses the impacts on production costs and the related emissions reductions when implementing CCS at the basic materials production plant. The analysis is from a value chain perspective, i.e., ranging from basic materials production to end-products for a range of product value chains in the cement, pulp, Waste-to-Energy, and refinery sectors.

Paper II presents and explores the Value Chain Transition Fund (VCTF), which is a novel, privately run, bottom-up financing mechanism that can be used independent of governmental intervention and that can bridge the cost and financing gaps by distributing the financial risk over a high number of actors. The VCTF could be used as a complement to current climate policy instruments, and it would allow industries to be front-runners in the transition within the coming decades. The paper explores the implications of such a fund, how it could be designed, and how it could be used to finance the transition in the EU-27 cement and steel industries.

Paper III analyses the transition of the EU cement industry towards CCS investments from a bottom-up, plant-level perspective, driven by plant responses to policy pressure, i.e., an increasing price of EU ETS emissions allowances. This work includes geographical aspects, such as proximity to CO_2 storage locations and availability of transport infrastructure, as well as regulatory aspects of the CCS chain.

Paper IV further analyses the EU cement industry transition. It not only includes the policy-push perspective to transition (as in **Paper III**), but also includes the consumer pull perspective, where consumers express a willingness to pay an extra premium for low-emissions cement. This is analysed using an Agent-based Model (ABM). In addition, cement producers are modelled as heterogeneous agents with varying risk-aversion levels, which indicates their willingness to invest under conditions of uncertainty.

Paper V compares past capital flows to the pace and levels of future investments required to meet near-zero emissions in materials production processes in the coming decades for the EU cement, steel, and petrochemical (steam crackers) industries. The historical pace of investment in industrial capital assets is evaluated, to assess whether they are sufficient to meet climate targets, and specifically, whether or not near-zero emissions production of materials by Year 2050 is feasible given historical investment rates.

Figure 1 provides an overview of the three main topics covered in Chapters 4–6 of this thesis, namely the cost gap, the financing gap, and the uncertainty in the transition.

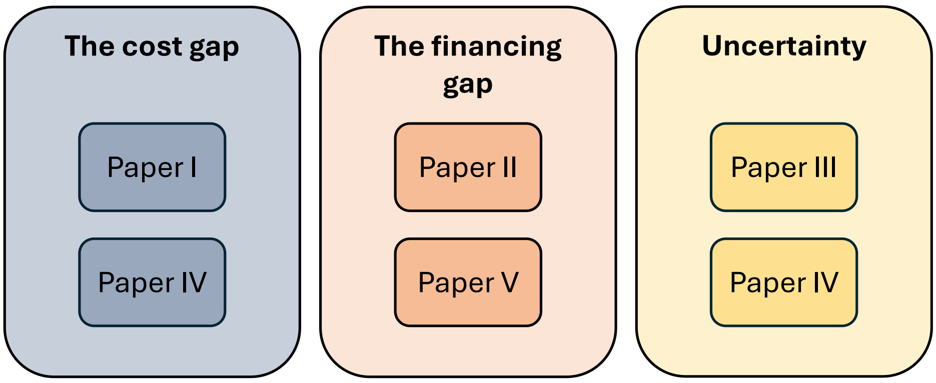

Figure 1. Overview of the three main topics (the cost gap, the financing gap, and uncertainty in the transition) covered in Chapters 4–6. Shown are also the papers from which the results in each chapter are retrieved.

CHAPTER 2

Background

This chapter introduces the following key aspects to this work: climate policy and complementary policy; value chains and supply chains; and regulatory aspects to consider when deploying capital-intensive mitigation technologies. The regulatory aspects are exemplified by the regulations for CCS.

2.1 Climate policy

In addition to the key themes addressed in this work, i.e., the cost gap, financing gap, and uncertainty (see Chapters 4–6), several other factors are critical for enabling the transition and the phasing-out of emissions-intensive materials production processes. Climate policy is one such factor which, other than in relation to the EU ETS, has not been explicitly examined in the following chapters. As mentioned above, policy instruments play a central role in facilitating the deployment of capital-intensive technologies and in overcoming the associated barriers.

Assigning a price to carbon is a central component of climate policies that are designed to decrease emissions (Haites et al., 2023; Swedish House of Finance, 2024). The EU ETS, which was launched in Year 2005, has proven to be the most-important policy instrument to regulate emissions from heavy industries over time, as these industries typically represent large point sources of CO_2 emissions (Sterner et al., n.d.). Although carbon pricing is a central component of climate policy, it has to date shown itself to be insufficient to drive the transformative change that is needed (Bataille et al., 2023; Haites et al., 2023; Nilsson et al., 2021a), as the prices for carbon emissions up to now have been too low and their future development remains uncertain. Furthermore, at the time of writing, the EU ETS has recently been reformed, with a reduction in the number of allowances on the market by 4.3% per year for the period of 2024–2027, with further increases in the reduction factor to 4.4% from Year 2028 (European Commission, n.d.-b). In addition, the free allocation of emissions allowances is phased out to strengthen the carbon price signal to emitters, thereby making carbon-intensive materials more expensive to produce. For materials that are competing on an international market, i.e., with materials produced outside of the EU, there is a risk of carbon leakage (International Carbon Action

Partnership, 2023). To avoid this, the EU has implemented a Carbon Border Adjustment Mechanism (CBAM), which will be phased in as the free allocation of emissions allowances is phased out (European Commission, 2023a). 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 contents of products (Cosbey et al., 2019). CBAM, which entered into its transitional phase in October 2023 and its definite compliance phase on January 1st 2026 (European Commission, 2023b), circumvents the assessment of carbon content, as it is primarily targeting basic materials, as well as some semi-finished products and hydrogen.

2.1.1 Complementary policies

In addition to carbon pricing, complementary policy measures will likely be required to support the transition and achieve net-zero emissions by mid-century. Although such policies are not explicitly analysed in this work, it remains important to consider their potential roles when analysing transition pathways. Commonly discussed complementary policy measures in the literature include:

- 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 an agreed-upon strike price, which ideally reflects the carbon price required to make an investment in low-carbon production economically viable. On the other hand, if the firm earns revenues above the strike price, the firm must return the difference to the regulator.
- 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. The 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 stated goal of the charge.

In addition, several possible support mechanisms and policy requirements that address cost and risk sharing have been proposed in the literature. These include:

- Governmental risk sharing and State funding during the early phases of the development and implementation of new technologies (Mazzucato & Rodrik, 2023). Examples of these are the EU Innovation Fund (European Commission, 2023c), the US Inflation Reduction Act (Internal Revenue Service, 2022), the Industrial Leap (Swedish Energy Agency, n.d.), and the reversed auctioning system for negative emissions operating in Sweden (Swedish Energy Agency, 2021);
- 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). The EU proposed new public procurement requirements in March 2026, which propose that at least 25% of the total volume of steel procured for use in buildings, infrastructure, and civil motor vehicles should be of low-carbon origin, and at least 5% of the volume of concrete and mortar used in buildings and infrastructure should be low-carbon (European Commission, 2026);

- 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);
- The issuance of Green Bonds, i.e., loans that are approved only for what are considered as "green projects" (Åhman et al., 2022; Chiappinelli et al., 2021; Monk & Perkins, 2020); and
- 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).

All of these measures can have more or less governmental involvement depending on their specific purposes. Most likely, a combination of the above-mentioned policies will be needed to achieve net-zero emissions by mid-century.

2.2 Value chains

In this work, 'value chain' refers to the creation of value and the profit margin that can be obtained from a certain supply chain business (see the original work by Porter (1985); and Mentzer et al. (2001), as well as references therein). Figure 2 shows a schematic overview of a simple product value chain. The concept of value chains is strongly linked to the concept of supply chains, which refer to the networks (typically, cross-sectoral) that facilitate the sourcing and primary production of materials, as well as the further processing and assembly and delivery of products or services to the consumer (see, for example Stevens (1990)).

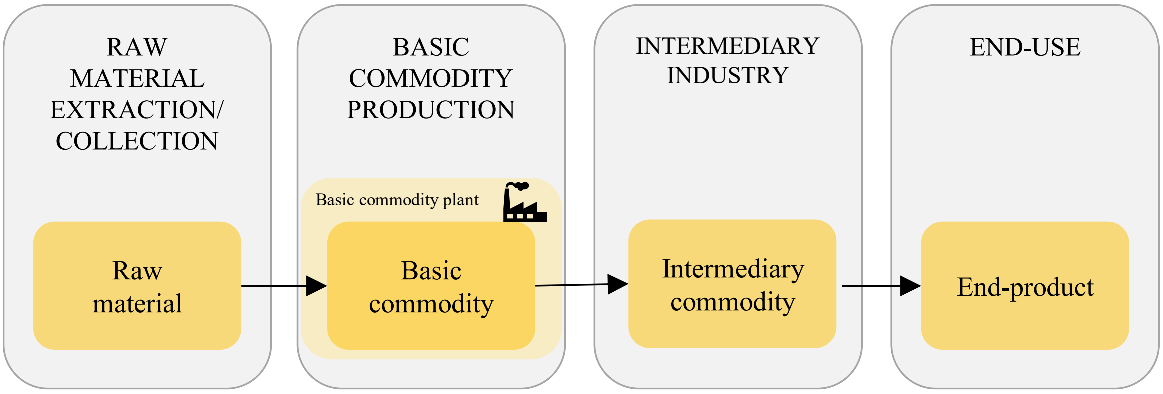

Figure 2. Illustration of a simple supply chain, proceeding from the extraction/collection of raw materials to the end-use for the basic commodity, and showing the actors participating in each step.

The participants in these supply chains need to act in a mutually dependent manner during the climate transition, as they cannot achieve the goal of net-zero emissions on their own (Stevens, 1990). If such mutual dependency does not occur, it can lead to co-ordination failures, as the widespread adoption of climate-mitigation technologies often requires simultaneous investments across the supply chain (Armitage et al., 2024). The primary producer relies on the users to adopt the less-emissions-intensive albeit more-costly product, while the users rely on the primary producer to take on the investments in low-emissions production capacity to reduce embedded emissions.

Most of the greenhouse gas (GHG) emissions originate up-stream in the value chain, while most of the value is realised down-stream. As an example, Clift & Wright (2000) have shown how primary resource industries give rise to environmental impacts that are disproportionate to the associated added value. This also means that when a carbon price is introduced the carbon price signal is unevenly distributed along the value chain, i.e., between different companies along the supply chain. This is certainly the case for many cement and steel supply chains, where the basic material largely is used in the building and construction industry and the automotive industry. For these supply chains, the embedded CO_2 emissions are mainly concentrated in the production of the basic materials (cement and steel), i.e., at the very beginning of the value chain, where the pricing of emissions occurs through the EU ETS system (*polluter pays principle*).

2.3 Regulatory aspects

The deployment of new transformative technologies that require extensive process changes and supporting infrastructure will most likely also require new regulatory interventions or new regulations. For the specific options in focus in this introductory essay, namely CCS and H-DRI, their deployment depends on technology-specific regulations, particularly in the case of CCS, given the complexity of the chain from capture to CO_2 transport and storage, which requires co-ordination among multiple actors. Thus, the following section addresses in particular the CCS-specific regulations.

All of the EU Member States have adopted the CCS Directive, which aims to “ensure that there is no significant risk of CO_2 leakage or damage to health or the environment and to prevent any adverse effects on the security of the transport network or storage sites” (European Commission, 2023d). The European Commission analyses the progress made by Member States in implementing the CCS Directive. The application of CCS policies and strategies for CCS implementation varies among the countries. The European Commission analyses the following categories: cross-border co-operation for CO_2 transport; national operational programmes or plans in place to support research, demonstration and deployment of CCS; measures in place to support financially the development of deployment of CCS; and further plans to support the appraisal of CO_2 storage sites, to prepare for the CO_2 transport infrastructure or for the establishment of CO_2 hubs and clusters. Depending on the levels of deployment of these various CCS policies, Member States will differ in their abilities to invest in and implement CCS in their industries. For example, for a land-locked country, cross-border co-operation for CO_2 transport is a prerequisite for the implementation of CCS if no national on-shore storage sites are available. Table 2 provides an overview of the EU Member States (and Norway) that have implemented (or plan to implement) the above-mentioned categories of CCS policies and strategies (European Commission, 2023d).

Table 2. Overview of the implementation of general CCS policies and strategies, announced cement CCUS projects, and CO_2 storage locations in the EU Member States and Norway. Shown are the countries that have implemented or planned (number of the four policies/strategies): >2 (green); ≤2 (yellow); and 0 (red). Note: Data collection made in Year 2024.

Country	Cross-border co-operation for CO_2 transport	National operational programmes or plans in place to support research, demonstration and deployment of CCS	Measures/programmes in place to support financially the development or deployment of CCS	Further plans to support the appraisal of CO_2 storage sites, to prepare for CO_2 transport infrastructure or for the establishment of CO_2 hubs and clusters	National CO_2 storage capacity[1]
Austria					No
Belgium					No
Bulgaria					Yes
Czechia					No
Croatia					Yes
Denmark					Yes
Finland					No
France					Yes
Germany					No
Greece					Yes
Hungary					No
Ireland					Yes
Italy					Yes
Latvia					No
Lithuania					No
Luxembourg					No
Netherlands					Yes
Norway					Yes
Poland					Yes
Portugal					No
Romania					Yes
Slovakia					No
Slovenia					No
Spain					No
Sweden					No

[1] This refers to announced CO_2 storage capacity. Several countries have potential for storing CO_2 but have no current plans to do so.

CHAPTER 3

Methodology

The key methods applied to address the cost gap, financing gap, and uncertainties associated with the transition of the cement and steel industries are briefly described in the following sections, with more-detailed descriptions provided in the respective papers. While the deployment of mitigation technologies, such as CCS and H-DRI, is often analysed from an industry perspective, focusing on the sites where these technologies are installed, such an approach does not fully capture the inter-dependencies that shape investment decisions. The transition depends on interactions between multiple actors and has implications along the product value chain, particularly for down-stream users of cement and steel. Therefore, most of the methodologies applied in this thesis adopt a value chain perspective which is impacted by the deployment of capital-intensive mitigation technologies, as illustrated in Figure 2.

3.1 The industry database

This thesis focuses on the cement and steel industries, where the cement sector comprises cement clinker plants and the steel sector is limited to primary steel production via the blast furnace-basic oxygen furnace (BF-BOF) route. All cement clinker plants and BF-BOF facilities covered by the EU ETS are included in the analysis. Plant-level data, including annual emissions and free allocations of emission allowances, are obtained from the EU ETS registry (European Commission, n.d.-g), while additional key characteristics, such as installed capacity and year of operation start, are derived from an updated version of the Chalmers Industry

Database (Rootzén & Johnsson, 2015). Figure 3 shows all currently operating cement clinker plants and BF-BOF plants in this data-set.

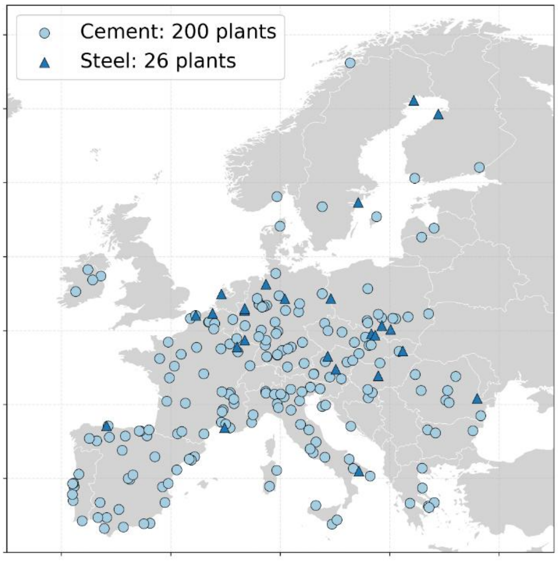

Figure 3. Overview and locations of cement clinker plants in the EU and Norway, and BF-BOF plants, as included in the Chalmers Industry Database.

Figure 4 shows the annual installed capacities obtained from the Chalmers Industry Database for: cement clinker (Figure 4a), and primary steel-making (Figure 4b). The results reflect only the initial installed capacity and exclude any expansions due to subsequent buildouts or renewals. The figure illustrates how across both industries, most of the capacity additions occurred during the 1960s and 1970s.

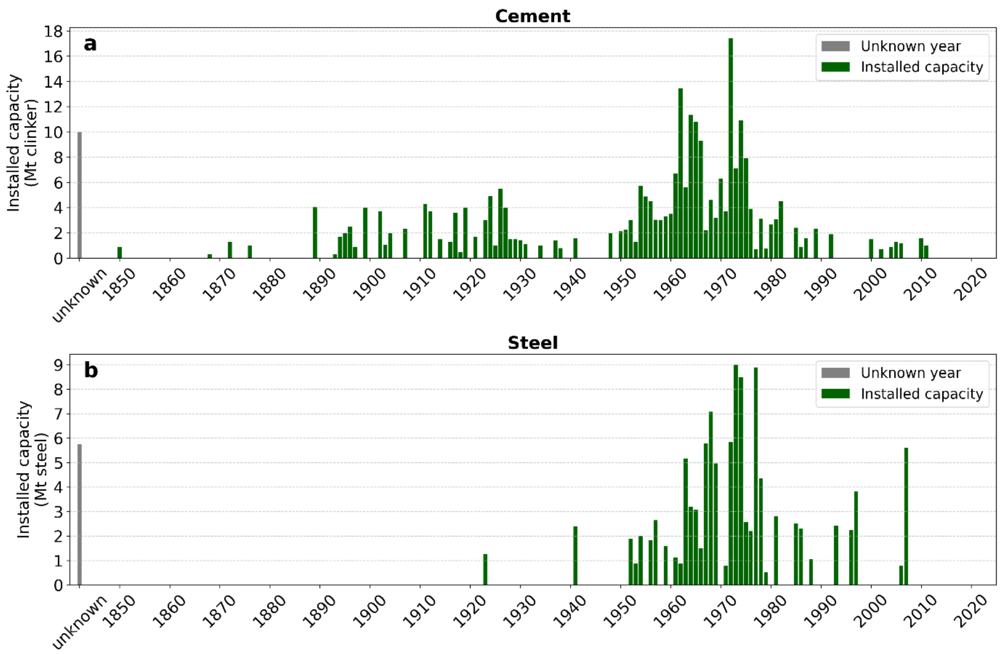

Figure 4. Development of the capacities of **a**) cement clinkers, and **b**) steel-making plants (BF-BOF), according to the data in the Chalmers Industry Database. For more details, refer to **Paper V**. The grey bar marks capacity with unknown operational start-up year.

3.2 Cost estimations

To analyse the cost gap and the financing gap, several of the appended papers rely on techno-economic assessments to determine the production costs of low-emissions materials. Thus, the following sections provide an overview of the cost estimations used in the work, including the concepts of overnight investment cost, production cost, and First-of-a-kind (FOAK) and Nth-of-a-kind (NOAK) cost estimates. Figure 5 provides an overview of the timeline.

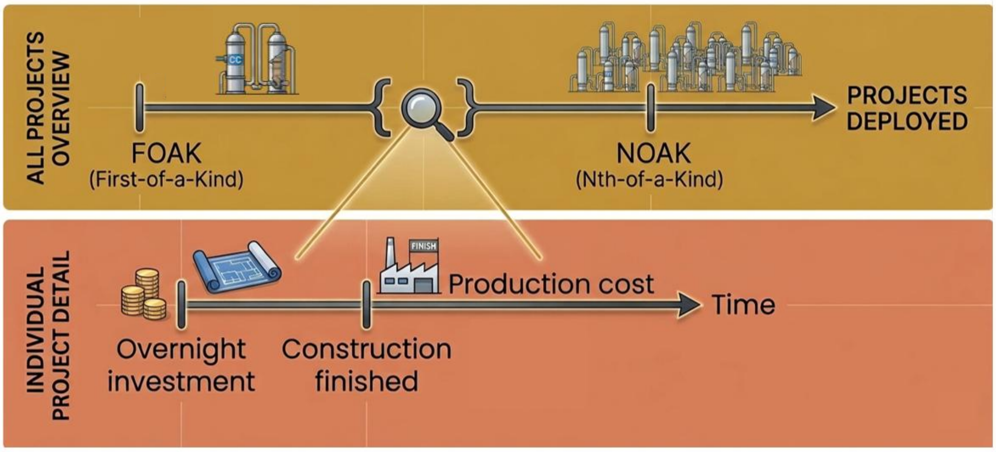

Figure 5. Timeline illustrating the progression from FOAK to NOAK costs (top panel), and its relation to an individual project, including the timings of and interactions between the overnight investment, construction period, and production costs (bottom panel). Illustration generated using an AI tool.

3.2.1 Overnight investments

To analyse the financing gap and the investment requirements for the transition of the EU cement and steel industries to near-zero emissions, this thesis applies the concept of overnight investment. Overnight investments represent 'overnight' types of costs, i.e., non-annualised pure capital expenditures, which capture only up-front investment costs without any additional costs or margins. In **Papers II** and **V**, this metric is used to estimate the scale of financing required for both conventional materials production and key decarbonisation measures, here meaning CCS and H-DRI. The resulting estimates enable a comparison between historical investment levels and the future capital required to achieve near-zero-emissions production of materials (**Paper V**).

To estimate the magnitude of past investments in capital-intensive assets in the cement and steel industries, data on the annual historical capacity expansion in each industry from the Chalmers Industry Database are used. Using these data, the timing and scale of major investments are estimated using data from the literature on overnight investment costs. Although technology investment costs have changed historically, the total investment made is estimated by assuming a fixed overnight investment cost per installed capacity (€/t clinker or steel) for each industry with adjusted cost-year using the Chemical Engineering Plant Cost Index (CEPCI). Obviously, industries are heterogeneous, having variations in plant design and configuration, resulting in a range of upfront investment costs per tonne of installed capacity. However, an average investment for each industry is assumed. Annual historical investment levels are calculated according to Equation (1):

$$I_t = \sum_i OC_i \cdot P_{i,t} \tag{1}$$

where *I* refers to the yearly historical investment in year *t*, *OC* refers to the overnight investment cost per unit of material production capacity, and *P* refers to the annual materials production capacity installed.

3.2.1.1 Future investment needs

The absolute investments required to transition from the current emissions-intensive material production to low-emissions production depend on the mitigation options used and their capital intensities. Thus, two types of scenarios are defined for mitigation option portfolios in the cement and steel industries to meet near-zero emissions:

1. A *transformative technology scenario* that relies heavily on the deployment of large-scale, capital-intensive mitigation technologies, i.e., no other mitigation measures are considered, and assuming the same demand for materials in Year 2050. For the cement industry this means into that all cement clinker plants adopt CCS, and that all of the BF-BOF capacity is replaced by H-DRI; and
2. A *portfolio-based scenario* that draws upon a broader mix of less-capital-intensive mitigation measures, including demand reductions through technological shifts, circular economy strategies, and improved material efficiencies.

These scenarios are used to assess how projected transition-related investment requirements compare with historical investment levels, thereby evaluating whether achieving near-zero-emissions material production in the EU by Year 2050 is consistent with the past investment dynamics in **Paper V**. It should be noted that mitigation measures outside the boundaries of basic industry, such as demand reduction, circular economy interventions, and material efficiency improvements, also entail costs that fall upon other actors in the value chain and are, therefore, not captured in this analysis.

3.2.2 Materials production costs

The cost of low-emissions material production is determined to analyse the cost gap, i.e., the difference in production costs between emissions-intensive and low-emissions materials. The materials production cost consists of two parts: 1) the costs related to everyday operation, i.e., the operational expenditures (OPEX); and 2) the costs related to the up-front overnight investment, which is then annualised, i.e., the CAPEX. The production cost, $\mathrm{C}_{\mathrm{s}}^{\mathrm{m}}$, for low-emissions materials, m, for each sector, s, is calculated according to Equation (2):

$$C_s^m = CAPEX_s + OPEX_s^{var} + OPEX_s^{fix} \tag{2}$$

where $CAPEX_s$ is the annualised overnight investment cost, based on a 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, see the respective papers). The CAPEX is annualised assuming a discount rate of 8%, and a technical life-time of 25 years in **Papers I-III**, while the discount rate in **Paper IV** varies depending on the producer's level of risk tolerance.

3.2.3 First-of-a-kind vs. Nth-of-a-kind

Materials production costs depend on the stage of technology deployment. First-of-a-kind (FOAK) installations are associated with higher costs, as key parameters remain uncertain and components are often project-specific, leading to additional expenses. As more plants are deployed, technological learning occurs across projects, resulting in cost reductions; these more-mature cost levels are referred to as Nth-of-a-kind (NOAK) estimates. Many techno-economic assessments focus on NOAK costs, reflecting expected future cost levels after learning has taken place, whereas FOAK costs capture the higher initial costs associated with early deployment. The appended papers use different cost estimates from the literature to estimate the materials production costs. **Papers I**, **II**, and **V** adopt a simpler approach and use fixed overnight investment cost assessments that are independent of plant capacity. Instead, **Papers III** and **IV** take into account economies of scale (i.e., that the cost is dependent upon the capacity of the plant) and uses a cost methodology described by Garðarsdóttir et al. (2018). The cost functions presented in these works represent NOAK costs for post-combustion, amine-based (MEA) absorption, assuming a 90% capture rate (except for **Paper IV**, which assumes a 100% capture rate). The cost functions originally presented by Garðarsdóttir et al. (2018) have been updated using the CEPCI.

To approximate the FOAK costs in this work, a contingency factor is applied to the NOAK costs, as large-scale, capital-intensive projects often experience substantial budget over-runs due to unforeseen costs, sometimes by as much as 100%–200% for CCS projects (Dubin, 2017; Fyen, 2023; Global CCS Institute, 2017). Figure 6 illustrates the cost development over time from FOAK to NOAK dependent on the contingency factor that is assumed (here illustrated with 100% or 200%) and the speed at which learning occurs (here shown with 3% representing a slower learning environment and 9% representing a faster learning environment).

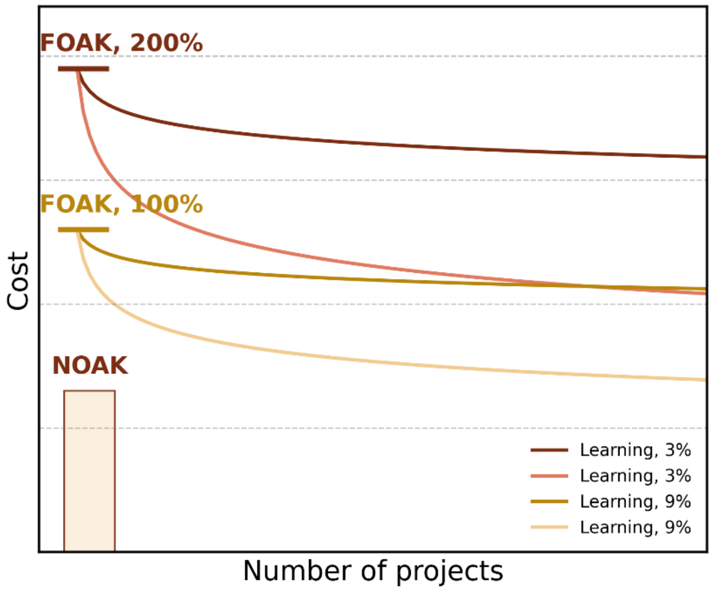

Figure 6. Estimations of the FOAK costs from the NOAK costs using 100% and 200% contingencies. Cost development from FOAK is assuming learning rates of 3% and 9%. Adapted from Beiron & Johnsson (2024).

In addition, Table 3 shows an overview of the cost assumptions made in each appended paper.

Table 3. Overview of the cost assumptions used in **Papers I–V**.

Paper	Cost estimate assumptions
I	Using cost data representing an average cement plant (IEAGHG, 2013).
II	Using cost data representing average H-DRI plants for the steel industry (Fischedick et al., 2014; Mission Possible Partnership, 2022; Vogl et al., 2018; Wörtler et al., 2013) and CCS for cement plants (Anantharaman et al., 2016; Gerbelová et al., 2017; IEAGHG, 2013; Liang & Li, 2012).
III	Using cost methodology based on flue gas volume and concentration, including economies of scale from Garđarsdóttir et al. (2018). **Paper III** includes only NOAK cost estimates.
IV	Using cost methodology based on fluegas volume and concentration including economies of scale from Garđarsdóttir et al. (2018). **Paper IV** includes FOAK cost estimates by applying a contingency factor of 100% to the NOAK cost estimates.
V	Using cost data representing average cement and steel plants, and CCS and H-DRI (EUROFER, 2019; Fischedick et al., 2014; IEAGHG, 2013; Obrist et al., 2021; Wörtler et al., 2013).

3.2.4 Cost propagation through the value chain

To analyse the impacts on the end-products of deploying CCS and H-DRI in the cement and steel industries, this work applies a product value chain perspective. Figure 7 shows a simplified illustration of the relationships between the product value chain and mitigation options (CCS and H-DRI). A product value chain analysis is then used to analyse how the costs of these capital-intensive technologies propagate through the value chain to the end-use. It is assumed that all production cost increases experienced by the basic materials 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. This is to showcase how the implementation of capital-intensive technologies impacts both basic materials (Equation 2) and as consumer prices (assuming that there is full cost pass-through and that no additional profit margins are imposed by any actor along the value chain). Hereinafter, the cost increase for a low-emissions product, as compared to the cost of a carbon-intensive product, is referred to as the *relative cost increase*. Importantly, the cost of the end-product not only includes the cost of the materials, but also the costs related to labour and energy use in the construction/production phase of all the materials and products along the value chain. This methodology is used in **Papers I** and **II**.

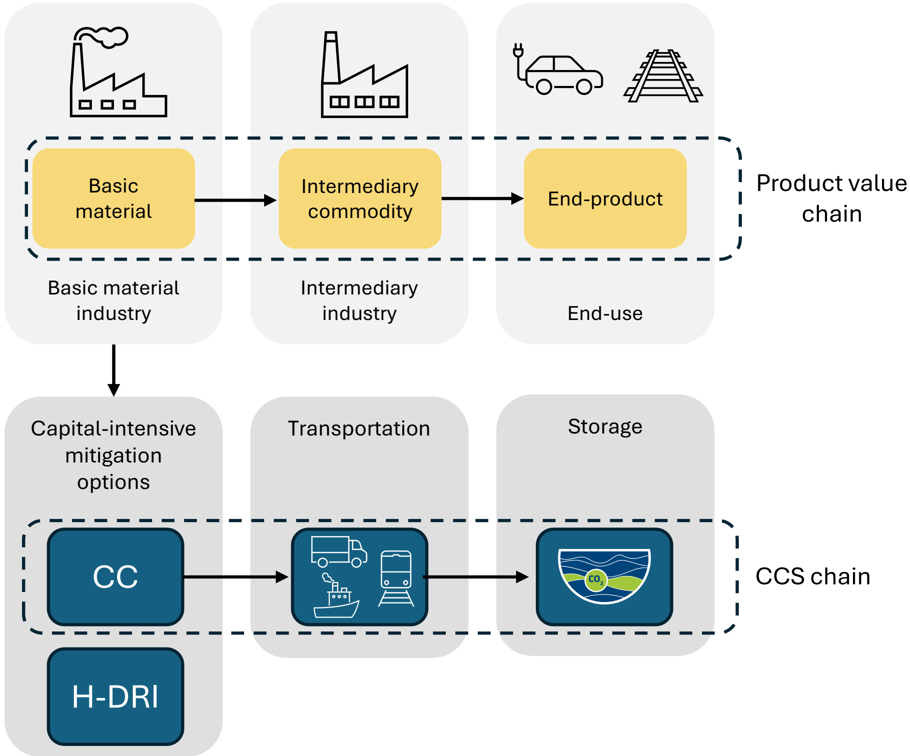

Figure 7. Schematic overview of the relationships between the product value chain and capital-intensive mitigation options (CCS and H-DRI), as well as the linkages between carbon capture and the full CCS chain, including CO_2 capture, transport, and storage. CC: Carbon capture.

The end-uses of the materials range from everyday single-use consumer products to more long-lived products, such as passenger vehicles and infrastructure elements, e.g., roads and railways. The end-users associated with these products also vary significantly, ranging from individual consumers to governmental agencies. In this thesis, two types of value chains are considered: cement to be used in the construction of a high-speed railway; and steel to be used in the manufacture of a passenger electric vehicle, to reflect the dynamics and impacts of end-users.

3.3 Simulating the industry transition

Papers III and **IV** adopt a simulation model approach to model the EU cement industry transition under conditions of uncertainty. Both papers evaluate cement producers' investment decisions in CCS due to policy-push, i.e., an increasing CO_2 price that closes the cost gap between conventional emissions-intensive production and low-emissions production. **Paper III** applies a higher spatial resolution than **Paper IV** and includes the availability of an infrastructure to transport CO_2 to a storage location, as well an analysis of the impacts of CCS-specific regulatory aspects. However, **Paper IV** accounts for more actor-specific heterogeneity, such as the levels of risk tolerance and willingness to invest under uncertainty of cement producers. In addition, **Paper IV** includes the consumer-pull perspective, whereby consumers express a willingness to pay an additional premium to cement producers for low-emissions cement, while **Paper III** only accounts for the policy-push perspective, i.e., increasing CO_2 prices. The actor representations (policy-maker, cement producer, and consumer) will be described in further detail in the following sections.

3.3.1 Policy-push: CO_2 price developments

Since the EU ETS is a central component of the EU industry transition, it is in this work modelled as a CO_2 price to assess its impacts on transition outcomes, i.e., the amount of CCS deployment. In the appended papers (**Papers I**, **III**, and **IV**), different CO_2 prices and price development trajectories are assumed. In **Paper I**, a fixed CO_2 price of 80 €/tCO_2 is assumed in the analysis, as the analysis is made for a single year. Instead, in **Papers III** and **IV**, CO_2-price trajectories are used. **Paper III** uses two (one "low" and one "high") steadily increasing CO_2 price trajectories, which means that with every year it becomes more expensive to emit CO_2. In contrast, **Paper IV** generates hundreds of annually fluctuating CO_2 price trajectories, so as to capture more effectively the market fluctuations and uncertainties regarding future ETS pricing. Figure 8 depicts the assumed CO_2 price trajectories.

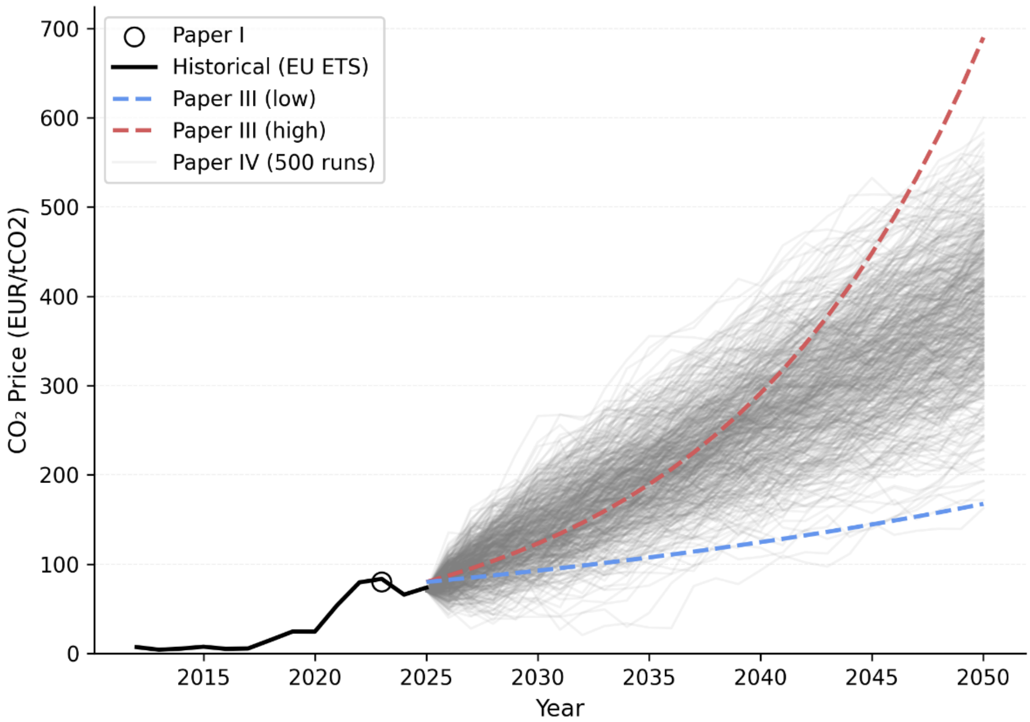

Figure 8. CO_2 price trajectories from **Paper I** (black circle), **Paper III** (red and blue for high and low price trajectories, respectively), and **Paper IV** (500 simulation runs represented in grey), with historical EU ETS prices from the period of 2012–2025 shown in black.

3.3.2 Heterogeneous cement producers

Paper IV models heterogeneous cement producers, to capture differences in strategic behaviours, where some actors act as front-runners, meaning that they are willing to invest under uncertain policy developments and profitability conditions, while others delay investment until policy frameworks that provide suitable incentives are in place. Each cement producer is modelled with a set of heterogeneous production-related properties, as well as properties related to its investment behaviour and risk tolerance. The production-related properties include production capacity, emissions intensity, and production cost for conventional cement, while the investment behaviour and risk tolerance include a risk-aversion level. The risk-aversion level (non-risk averse, risk-neutral, and risk-averse categories) is represented by a discount rate (5%–17%) that is used when annualising the capital investment. A lower discount rate (high risk tolerance, i.e., non-risk-averse cement producer) means that the producer places a higher value on future benefits and is willing to invest even when the returns are expected to be lower. A higher discount rate (entailing low risk tolerance, i.e., risk-averse producer) places a lower value on future cost savings and, therefore, requires higher expected returns to justify an investment. The plant properties of the producers are randomly distributed based on the intervals presented in Table 4.

Table 4. Randomly distributed cement plant properties.

Plant properties	
Production capacity per plant	1,000–2,000 kt cement/year
Emissions factor (conventional cement)	0.7–0.9 tCO_2/t cement
Conventional cement production cost	50–55 €/t cement
Investment-/risk aversion properties	
Discount rate	5%–17%
Risk-aversion level	Non-risk-averse (5% to <9% discount rate) Risk-neutral[a] (9% to <13% discount rate) Risk-averse (13%-17% discount rate)

[a]Indeed, all cement producers face some degree of risk, and the term “risk-neutral” does not imply that these investments made by these producers are risk-free.

3.3.3 Consumer demand and willingness to pay

Consumers differ with respect to their willingness to pay for low-emissions cement, with some willing to pay a premium for a product that has lower associated emissions but otherwise has identical properties (Alberini et al., 2018). This segmentation of end-users reflects empirical observations that actors in certain market niches (e.g., green building certifications and public procurement) are willing to pay higher prices for low-emissions materials. To illustrate this, the demand for cement in **Paper IV** is divided into five consumer segments (see Table 5), based on Rogers’ diffusion of innovation framework (Rogers, 2003). While Roger’s categorisation of societal groups is complex, it is here used simply to capture the diversity of consumers and their varying levels of willingness to pay for low-emissions materials on the market. The five consumer segments described in Rogers (2003) are: *innovators*, *early adopters*, *early majority*, *late majority*, and *laggards*. The segment sizes are modelled to remain constant over time. The consumer segments express different levels of willingness to pay for low-emissions materials, which are represented in the model through segment-specific discount rates that are applied to evaluations of low-emissions projects. Innovators and early adopters are assigned lower discount rates, reflecting a greater willingness to invest in future benefits, which means that they perceive the present value of low-emissions cement production as lower, compared with segments that have higher discount rates, such as the laggards. As a consequence, innovators effectively experience low-emissions materials as being less-expensive, as compared with laggards, who are more short-term-oriented and, thus, perceive higher costs.

Table 5. Consumer segments' initial shares of the population and the discount rates used to assess willingness to pay (Rogers, 2003). The initial segment size is constant throughout the simulation.

Consumer segment	Segment size in Year 2026 (%)	Discount rate for decision making (%)
Innovators	2.5	3
Early Adopters	13.5	5
Early Majority	34	10
Late Majority	34	15
Laggards	16	20

3.3.4 Making an investment decision

Each cement producer described in **Papers III** and **IV** makes a yearly evaluation as to whether they should invest in CCS. In **Paper III**, the cement producer makes this investment decision instantaneously by evaluating the policy conditions (meaning the CO_2 price) during the evaluation year. However, in **Paper IV**, cement producers make projections of the CO_2 price in the coming years, to evaluate if and when a CCS investment becomes profitable, with profitable meaning that it is cheaper to produce cement with CCS than emitting CO_2 and paying for emissions allowances, as expressed by Equation (3):

$$C_{CCS} < C_{conventional} + C_{emissions} \quad (3)$$

where C_{CCS} is the cost of producing cement with CCS (€/t cement), $C_{conventional}$ is the cost of producing conventional cement (€/t cement), as listed in Table 4, and $C_{emissions}$ is the cost of emitting according to the yearly CO_2 price.

The cost for producing cement with CCS is determined according to Equation (4):

$$C_{CCS} = TCR \cdot \frac{i_{plant}}{1-(1+i_{plant})^{-L}} + OPEX + C_{T\&S} \quad (4)$$

where *TCR* is the total capital required for the capture unit (described further in Section 2.5.2), i_{plant} is the plant's discount rate based on a risk-aversion level, L is the economic life-time (assumed to 25 years), *OPEX* is the operational expenditures, which include both fixed and variable costs (described further in Section 2.5.5), and $C_{T\&S}$ is the cost for transporting and storing CO_2. The TCR in **Papers III** and **IV** is dependent upon economies of scale, although **Paper III** assumes NOAK costs through all years while **Paper IV** assumes FOAK costs at the start of the simulation and learning between projects, thus resulting in NOAK costs by the end of the simulation. The cost for transporting and storing CO_2 is plant-specific in **Paper III**, whereas it is simplified to a generic number for all plants in **Paper IV**. As the CO_2 price is steadily increasing in **Paper III**, this implies that when a cement plant makes an investment decision regarding CCS [according to Equation (3)] it will thereafter always be profitable with CCS compared to paying for emissions allowances. However, this is not the case in **Paper IV**, where the CO_2 price is uncertain and fluctuates over time. Cement producers, therefore, base their decisions on expected rather than realised CO_2 prices, which may lead to incorrect projections and investment decisions regarding CCS even when it is not ultimately profitable. Thus, the dynamics in **Paper IV** are more complex than in **Paper III**, and cement producers are modelled to go bankrupt if making unprofitable investments.

In addition, in **Paper IV**, if the policy-push evaluation does not favour an investment in CCS, the cement producer agent evaluates whether there are consumers that are willing to pay a sufficiently high premium for low-emissions cement, in order to cover the cost gap. As a result, any CCS investments attributed to consumer demand show an additional uptake that would not have occurred through policy alone, thereby accelerating the transition. Equation (5) expresses the consumer-pull evaluation:

$$C_{CCS} - Premium < C_{conventional} + C_{emissions} \tag{5}$$

This potential price premium provides an additional revenue stream that can close the cost gap identified in the policy-push evaluation, making the investment in CCS financially viable earlier than if considering only the CO_2 price. Moreover, cement producers that invest in CCS in response to the consumer-pull effect are rewarded with long-term contracts, ensuring a stable income stream over the entire simulation period (thus limiting uncertainty). To quantify each consumer segment's willingness to pay – and, by extension, the premium price that a cement producer can receive for supplying those consumers – the model calculates the premium as the difference between the consumer's estimation of the cement production cost (using the consumer's discount rate, shown in Table 5) and the producer's estimation (using the producer's discount rate, shown in Table 4), according to Equation (6). For example, if the producer's discount rate is 10% and the consumer's discount rate is 5%, the consumer will place a higher value on future cost savings, resulting in a positive premium for low-emissions cement, which the consumer is willing to pay to the producer.

$$Premium = \frac{TCR}{P} \cdot \left(\frac{i_{producer}}{1-(1+i_{producer})^{-L}} - \frac{i_{consumer}}{1-(1+i_{consumer})^{-L}} \right) + OPEX_{fix,producer} - OPEX_{fix,consumer} \tag{6}$$

where P is the plant production capacity, i is the individual discount rate for the producer or consumer, and L is the economic life-time.

CHAPTER 4

The cost gap

The production cost of low-emissions basic materials like steel, and cement is typically higher than that of conventionally produced materials due to increased capital and operational expenditures. Low-emissions materials and products are typically substitutes for conventional alternatives and, aside from lowering emissions, offer no obvious additional benefits to end users. Thus, firms' ability to establish a viable business case is limited, as they must compete with cheaper emission-intensive materials on the market. This chapter addresses the production cost of materials and products from a value chain perspective.

4.1 Quantifying the cost gap

Figure 9 shows the cost gap between carbon-intensive cement and steel, and their low-emissions counterparts in Figure 9, a and b, respectively. It shows that cement produced with CCS is more than 200% more expensive than carbon-intensive cement, and that hydrogen-based steel is 50% more expensive to produce than conventional steel. This illustrates the challenges and market-related barriers that arise when low-emissions materials must compete with cheaper carbon-intensive materials. It also points to the challenges associated with making low-emissions materials profitable, as they need to be sold at higher prices to consumers, assuming that consumers with such a willingness to pay for emissions reductions exist. Obviously in this example, cement faces a more-significant relative cost increase compared to steel (194% compared to 50%), which implies that certain materials might face greater market barriers than others. However, the cost gap depends strongly on the underlying cost assumptions, for example regarding FOAK and NOAK cost assumptions, and the results in Figure 9 should therefore be interpreted as illustrative rather than definitive.

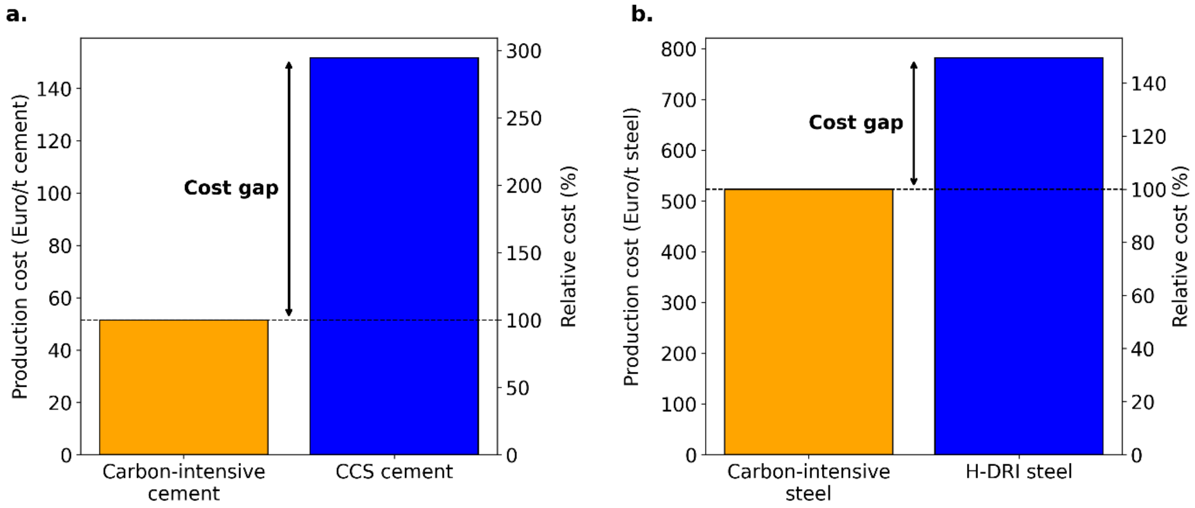

Figure 9. Example of the gaps in production costs between: **a**) carbon-intensive and low-emissions cement produced with CCS; and **b**) conventional steel and steel produced with H-DRI.

4.2 Closing the cost gap

Measures that can contribute to closing the cost gap between conventional and low-emissions materials, include policy instruments, such as carbon pricing. Beyond these supply-side policy interventions, the following sections analyse the roles of product value chain dynamics and demand-side factors, such as consumer willingness to pay, in addressing this cost gap.

4.2.1 Added value and environmental impacts along the value chain

Clift & Wright (2000) have shown that the majority of environmental impacts arise in the initial stages of the value chain, whereas most of the added value is generated further down-stream. Figure 10 shows the emissions and costs along the value chain for the cement-to-railway case, which uses emissions-intensive cement and concrete (results adapted from **Paper I**). The results reveal patterns similar to those described by Clift & Wright (2000), in that most of the emissions associated with the railway occur up-stream during material production (Steps 1–3), while the majority of the costs arise down-stream during the construction phase (Step 4). This highlights a disproportionate relationship between where emissions occur and where economic value is generated.

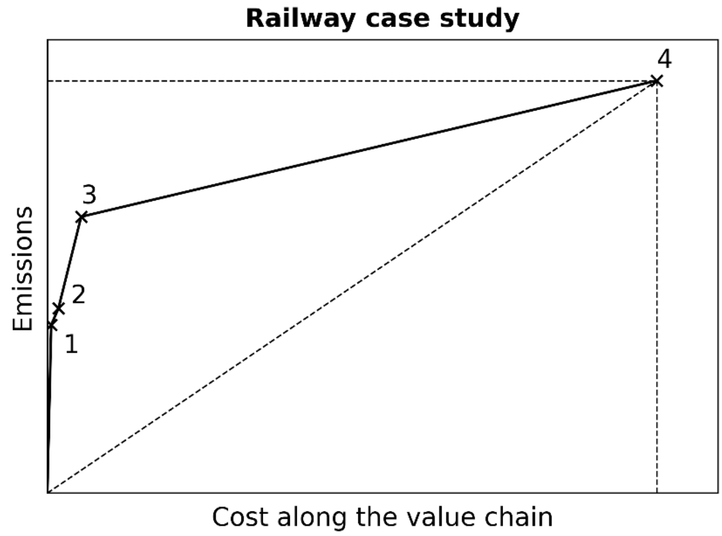

Figure 10. Costs and emissions along the value chain using the results from the high-speed railway case study in **Paper I**. The indicated steps are: 1, cement production; 2, concrete production; 3, materials associated with the railway infrastructure; and 4, construction of the railway, including materials, fuels, labour, and other inputs.

This has important implications for decarbonisation across value chains. Down-stream actors are generally able to add higher absolute profit margins with relatively limited impact on the final product price, as the final product is more complex and more costly, which dilutes the contribution of individual costs. In contrast, basic materials producers operate in competitive markets, where products are relatively homogeneous and low-cost in relation to the final product (as illustrated in Figure 10). Consequently, if basic materials producers internalise the additional costs, for example those associated with mitigation options, this will lead to substantial increases in the production cost of the basic material itself (see Figure 9), making it challenging for basic materials producers to absorb fully these costs.

Materials also account for a large share of the total environmental impact of end-products, which implies that deep decarbonisation of down-stream sectors will ultimately be dependent upon the decarbonisation of up-stream materials production. This creates a structural challenge, as capital-intensive mitigation options in basic materials industries significantly increase production costs, while the ability to translate these costs into equivalent value creation remains limited. Thus, value chains are characterised by a misalignment between responsibility for emissions and economic rewards, where the most emissions-intensive and difficult-to-abate activities are also those with the weakest profit margins, representing a fundamental barrier to large-scale industrial transition.

4.2.2 Value chain impacts: Cost increase on end-products

The deployment of capital-intensive mitigation options increases the cost of basic materials, posing a challenge for producers. However, as these materials are ultimately incorporated into end-products, the resulting cost impacts need to be assessed from a value chain perspective, in order to capture their full implications. Figure 11 shows the impacts on costs and emissions for two value chains: (1) cement to a high-speed railway, and (2) primary steel to a passenger EV. The results show that while the cost increases for cement and steel are substantial (194% for cement and 57% for steel) when deploying CCS and H-DRI, respectively, the resulting cost increases for the railway and passenger EV remains small when these costs are passed down along the value chain (assuming full cost pass-through and no additional margins). At the same time, the implementation of CCS and H-DRI results in substantial reductions in emissions related to the production of cement and steel (86% for cement and 91% for steel), respectively, as well as across the value chain (35% for the railway and 46% for the passenger EV). This occurs because the basic commodity accounts for a large share of the total emissions but only a small fraction of the final product value, as also shown in Figure 10. In **Paper I**, other industries and related value chains are also explored, and the results show that for most industries, the cost increase is drastically reduced already at the second actor along the value chain. These results underscore the importance of a value chain perspective in capturing the full implications of deploying capital-intensive mitigation options, and demonstrate that these mitigation options deliver substantial emissions reductions at low cost.

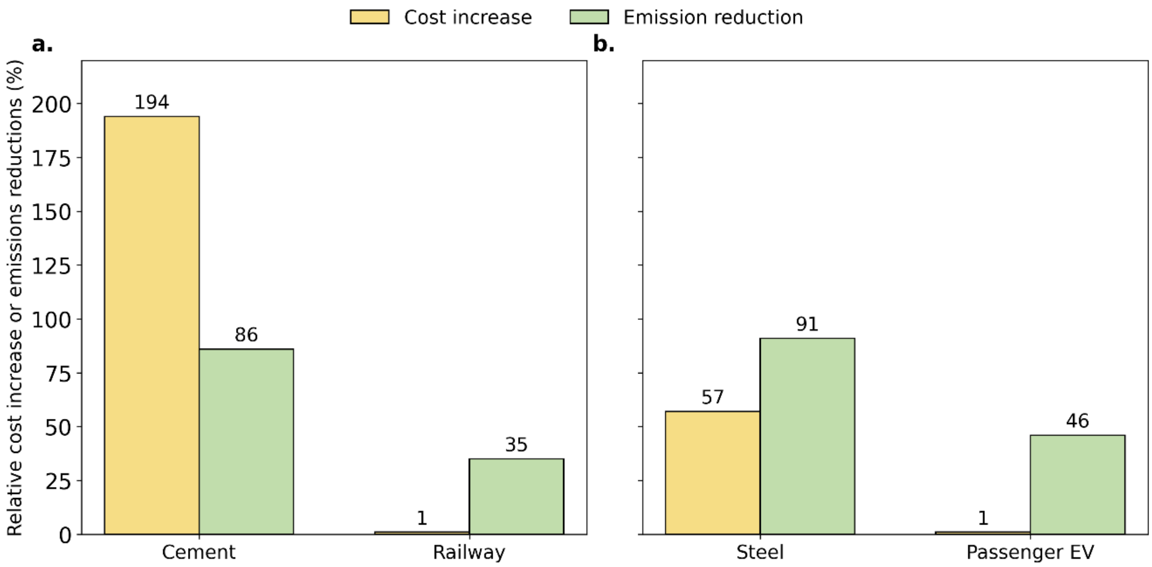

Figure 11. Impacts on costs and emissions in the first and final steps of the value chains considered in this work: **a**) cement to a high-speed railway (results from **Paper I**); and **b**) primary steel to a passenger electric vehicle (EV) (results from **Paper II**).

This work does not quantify the cost impact of fully decarbonising a product, i.e. decarbonising all materials and services associated with an end-product. However, as shown in Figure 10, the costs associated with materials (Steps 1–3) are relatively low in the railway case study, while construction-related costs, such as those for labour, fuel, and other inputs, dominate the total cost of the railway. This suggests that decarbonising *all* materials may lead to relatively limited increases in total costs, while potentially achieving substantial emissions reductions as shown for a single material in Figure 11.

4.2.3 Value chain opportunities

From a value chain perspective, there is a clear mismatch between the points along the value chain where emissions occur and where value is added. Seemingly, basic material producers must take on significant costs (compared to their products' added value) to reduce emissions, while they are unaware as to what extent they can pass on the costs to the end-consumer. However, if the additional costs were to be passed down-stream along the value chain, **Paper I**, **Paper II** and other studies (for example, Rootzén & Johnsson (2016a), Rootzén & Johnsson (2016b), Subraveti et al. (2023), and Klement et al. (2021)) have shown that the cost impact on end-products would be relatively weak. This is because basic materials such as steel and cement typically account for only a limited share of the total production costs, meaning that cost increases at the materials level are diluted as they pass along the value chain. Similarly, Neuhoff et al. (2014) have shown that also increased carbon pricing for emissions-intensive steel and cement has only a limited impact on the final consumer prices. As a result, even substantial increases in production costs at the material stage (arising from deploying capital-intensive mitigation options or sufficiently high carbon prices) translate into relatively minor price changes for the end-user. This has important implications for policy design, and suggests that carbon pricing mechanisms, such as the EU ETS, can help close the cost gap between conventional and low-emissions materials without significantly affecting consumer prices. From a value chain perspective, this means that ambitious carbon pricing can drive decarbonisation up-stream in the value chain while remaining economically manageable down-stream. However, this still relies on predictable policy signals, where the polluter-pays principle in practice has often been undermined by a lack of policy predictability, thereby limiting its effectiveness and highlighting the need for complementary drivers.

Even though this work shows that the cost gap between conventional and low-emissions end-products is small, basic materials producers remain dependent upon sufficient consumer demand and willingness to pay for such products. There are several emerging initiatives to address this. For example, off-take agreements between producers and down-stream actors are gaining traction as a mechanism to share risks and enable early investments in low-emissions production. The fossil-free steel company Stegra has entered into such agreements to secure demand and reduce uncertainty regarding its low-emissions steel. Similarly, at the policy level, there are ongoing discussions within the European Commission on the creation of lead markets for low-emissions materials. These could be established through instruments such as green public procurement standards and mandatory quotas, as recently proposed for cement and steel[2]. Such measures would help to generate predictable demand and support the market uptake of low-emissions materials. In addition, there are several emerging initiatives to address the mismatch between where in the value chain emissions occur and where purchasing decisions are made. One example is the adoption of Science Based Targets, through which companies voluntarily commit to reducing not only their direct (Scopes 1 and 2) emissions but also indirect (Scope 3) emissions along the value chain, which creates opportunities for down-stream actors to engage with, and support, low-emissions materials producers.

4.2.4 Consumers' willingness to pay for low-emissions products

To close the cost gap and reduce the investment risk between conventional and low-emissions materials, consumers' willingness to pay for low-emissions products can play an important

[2]See European Commission (2026).

role. By increasing the demand for such materials, products or services, consumers can exert a pulling effect on the market, thereby complementing policy efforts and encouraging industry to accelerate the transition toward low-emissions materials production and securing an outlet for said materials.

It has been shown that consumers are willing to pay a premium for low-emissions products (Alberini et al., 2018), indicating a willingness to pay more for comparable products that offer reduced emissions. Figure 12 shows the results from **Paper IV** regarding CCS deployment over time in the EU cement industry in line with an increasing CO_2 price (Figure 12, a and c), and due to an increasing CO_2 price as well as with consumers being willing to pay an additional premium for low-emissions cement (Figure 12 b and d). For detailed model description refer to **Paper IV**.

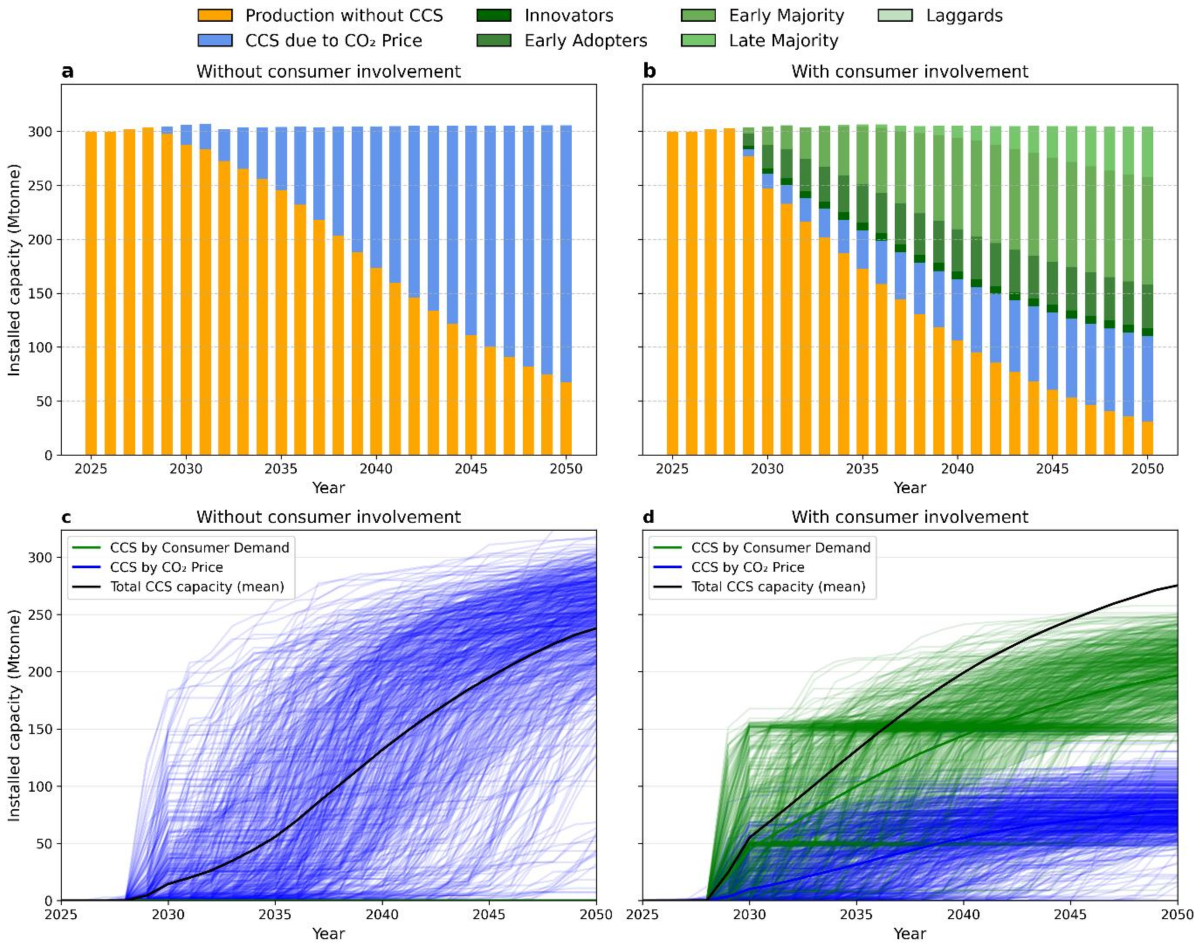

Figure 12. CCS diffusion without (**a**, **c**) and with (**b**, **d**) consumer involvement. Panels **a** and **b** show the average results for 500 model runs in an agent-based simulation model (**Paper IV**) without and with consumer involvement, respectively. Panels **c** and **d** show all of the individual results over 500 model runs (the solid black line in panels **c** and **d** corresponds to the average installed CCS capacity).

The results show that CCS deployment is accelerated when consumers are willing to pay a premium for low-emissions cement (thus closing the cost gap), resulting in earlier adoption (by 6 years on average to reach the same level of decarbonisation) and a higher number of plants adopting CCS by Year 2050. Overall, 84% of plants decarbonise by Year 2050 with consumer involvement, as compared with 72% without consumer involvement. The results show that consumer involvement leads to earlier and more-widespread adoption of CCS. For example, 43% of plants have adopted CCS by Year 2035, as compared with 18% without consumer involvement. This results in lower cumulative emissions and accelerates cost reductions through learning effects. In addition, a certain level of willingness to pay among consumers results in a hedging effect for industry actors by reducing the investment risk, as consumers provide a secure market outlet for low-emissions cement and enable firms to make early investments and act as front-runners in the transition.

The results indicate that consumers can exert substantial influence over the transition to low-emissions cement production, where 84% of consumers herein express some sort of willingness to pay for low-emissions materials. In practice, this influence might be stronger in value chains in which the demand is concentrated among large, co-ordinated buyers, such as corporate or governmental consumers, who can leverage procurement power to create early markets for low-emissions materials. Such actors can effectively reduce the market risk for plants that are adopting capital-intensive technologies such as CCS, by providing a stable demand and potentially higher prices, thereby facilitating investment in decarbonisation technologies. However, consumer influence is dependent upon the market structure. In the cement value chain, the concentration of demand and the relatively direct link between consumers and suppliers enhance the potential for demand-driven transitions. In other sectors in which materials are more fragmented within the value chain, or where final consumer preferences are filtered through multiple intermediaries, aggregating the demand signals is more challenging, making it increasingly difficult for consumer choices to drive decarbonisation.

CHAPTER 5

The financing gap

CCS and H-DRI require substantial upfront capital investments (Rissman et al., 2020), and achieving the scale of investment required for the transition is challenging, as these technologies typically are challenging to finance through conventional channels. While public funding mechanisms exist, they are far from being sufficient to cover the full investments required to transition heavy industry to near-zero emissions by mid-century. Thus, achieving the scale of investments required for the transition relies on the mobilisation of private capital. The International Energy Agency (2024) has suggested that the private sector needs to contribute around 75% of the total financing required for the energy transition, while the public sector needs to take enabling and catalytic roles at the start of the transition. This chapter addresses the issue of financing capital-intensive technologies.

5.1 EU funding mechanisms

The following section gives an overview of currently available EU funding mechanisms. These mechanisms pursue different objectives, such as supporting First-of-a-kind, flagship and demonstration projects, and promoting a just transition. Many of these funding mechanisms are directed towards First-of-a-kind projects, meaning that they are not designed to support the large-scale deployment of CCS and H-DRI required to decarbonise the entirety of the EU cement and steel industries. In addition, the existing EU funding mechanisms are often directed towards a wide range of sectors, not only the hard-to-abate industries.

The *EU ETS* raises revenues through auctioning emissions allowances. The system has raised over €245 billion since the cap-and-trade system started in Year 2013 and up to late-2025, and Year 2024 alone resulted in €39 billion of revenues (European Commission, 2025a). These revenues are largely distributed directly to EU Member States (roughly two-thirds), and the remainder is assigned to EU support schemes, such as the Innovation Fund (since Year 2020), the Modernisation Fund (since Year 2013), the Resilience and Recovery Facility (REPowerEU, since Year 2023), and the Social Climate Fund (since Year 2025). However, less than 5% has so far been re-invested in industrial decarbonisation at the national level (ESG Today, 2026).

In Year 2023, the EU Member States received €33 billion from the EU ETS, out of which €30.9 billion must be used for climate action and the energy system transformation. However, this obviously includes many sectors and not only industry. In this specific year, €22.2 billion were used (with the remainder being saved for coming years), and "only" €0.7 billion were used to fund industry decarbonisation initiatives (European Commission, 2025a).

The *EU Innovation Fund* supports decarbonisation efforts in the energy and industrial sectors. Revenues from 530 million ETS allowances will enter the fund, which is estimated to amount to approximately €40 billion for the period of 2020–2030, depending on the auctioning prices of emission allowances (European Commission, 2025b). Roughly €12 billion have been awarded to projects to date (European Commission, n.d.-e). The Innovation Fund focuses on highly innovative technologies and flagship projects that can bring significant emissions reductions within the topics of energy-intensive industries, renewable energy, energy storage, CCUS, and net-zero mobility and buildings. Thus, it does not focus on large-scale diffusion of decarbonisation technologies, but instead acts as a catalyst for demonstration projects (although a share of the funding can cover operational expenditures, as was also permitted under the previous NER300 programme, which supported both capital and selected operational costs; however, it did not succeed in attracting projects for industry). Since the start of the EU Innovation Fund, 23 projects have received funding within the chemical sector, 16 within the cement and lime sector, and 8 within the iron and steel industries, amounting to €4.89 billion.

The *EU Just Transition Fund* is designed to address the social and economic effects of the transition, focusing on regions that face greater challenges in their transition. With funds of €19.7 billion, it is expected to mobilise an additional €7.3 billion of national co-financing (European Commission, n.d.-f).

5.2 Mobilising private investment through the EU

In addition to the above-mentioned EU funding mechanisms, the EU bridges market failures where projects are deemed too risky to take on by private investors, such as through *Important Projects of Common European Interest (IPCEI)*, *InvestEU* and *the Industrial Decarbonisation Bank*, which are described below.

The *IPCEIs* are state-aid frameworks that allow Member States to jointly finance large-scale, cross-border strategic projects (such as those in energy and industrial value chains) where market failures prevent private investment. Projects that are deemed by the EU to have this status can receive levels of public support that would normally be in conflict with the state aid rules of the EU's internal market. Unlike centrally managed EU funds, IPCEIs do not have a fixed budget, with funding levels determined by participating Member States and private co-financing on a project-by-project basis (European Commission, n.d.-c).

InvestEU is an EU investment programme that is designed to mobilise private investments in sustainable infrastructure, research and innovation, small- and medium-sized enterprises (SMEs) and skills development. It leverages an EU budget guarantee of €26.2 billion (out of which €6.6 billion is allocated to research, innovation and digitisation), with the aim of triggering €372 billion of private investments in these four areas (European Union, n.d.).

As part of the EU's broader strategy to mobilise capital for the industrial transition, the *Industrial Decarbonisation Bank* is being proposed as a new financing vehicle aimed at mobilising up to €100 billion in investment for the decarbonisation of hard-to-abate industrial sectors. Rather than functioning as a traditional grant programme with a fixed budget, it is intended to aggregate resources from several existing and evolving EU instruments, including funds from the *Innovation Fund*, additional revenues from parts of the EU ETS, and enhanced investment mobilisation through *InvestEU (European Commission, n.d.-d)*.

5.3 Financing required for CCS and H-DRI deployments

This section estimates the amount of financing that is required to transition the EU cement and steel industries to near-zero-emissions production. In addition, historical capital flows for conventional, capital-intensive technologies (such as cement kilns and BF-BOF) are estimated for each industry and compared with the investment rates required to meet climate targets by Year 2050, in order to assess whether historical investment rates are sufficient. Figure 13 shows the results from **Paper V** regarding the estimated historical investments (in green) and the estimated future investments required to achieve near-zero emissions (grey boxes with average values in the dashed line) for the (a) cement, and (b) steel industries. The S1 box estimates a range of up-front capital investments that are needed if all current cement clinker capacity deploys CCS or H-DRI for the cement and steel industries, respectively (as for the *Transformative technology scenario* explained in the *Methodology* section), with the upper and lower limits of the box representing different overnight investment cost estimates from the literature. The S2 box instead represents a scenario with a broader portfolio of mitigation options, such as clinker replacements and increased circularity of materials to reduce the need for primary materials (as for the *Portfolio-based scenario* as explained in the *Methodology* section). The blue bars indicate how far each industry could progress towards the investment requirements for Year 2050, given the historical, annual, country-based investment paces based on: the maximum investment ever made in a year; the 10-year rolling average; and the 25-year rolling average (depicted by the three blue bars, respectively). The results show that, at the maximum historical investment pace, the steel industry could raise sufficient capital to transition, as their investment levels exceed the average S1 line (assuming that the technologies are not more expensive than indicated by the upper range of the S1 box). In contrast, the cement sector falls short of the S1 target for all historical investment paces analysed. Steel also falls short at the 10-year and 25-year average paces. This emphasizes the need to push for less-capital-intensive pathways to reach near-zero emissions, so as to reduce the levels of investment required to transition. In addition, the magnitude of the future investment need is significantly larger in the coming 25 years than in any prior 25-year period (comparing the dashed line with the green bars) for both cement and steel, highlighting the magnitude of the challenges to come for those industries. This points to an unprecedented need to mobilise capital over a relatively short time-frame.

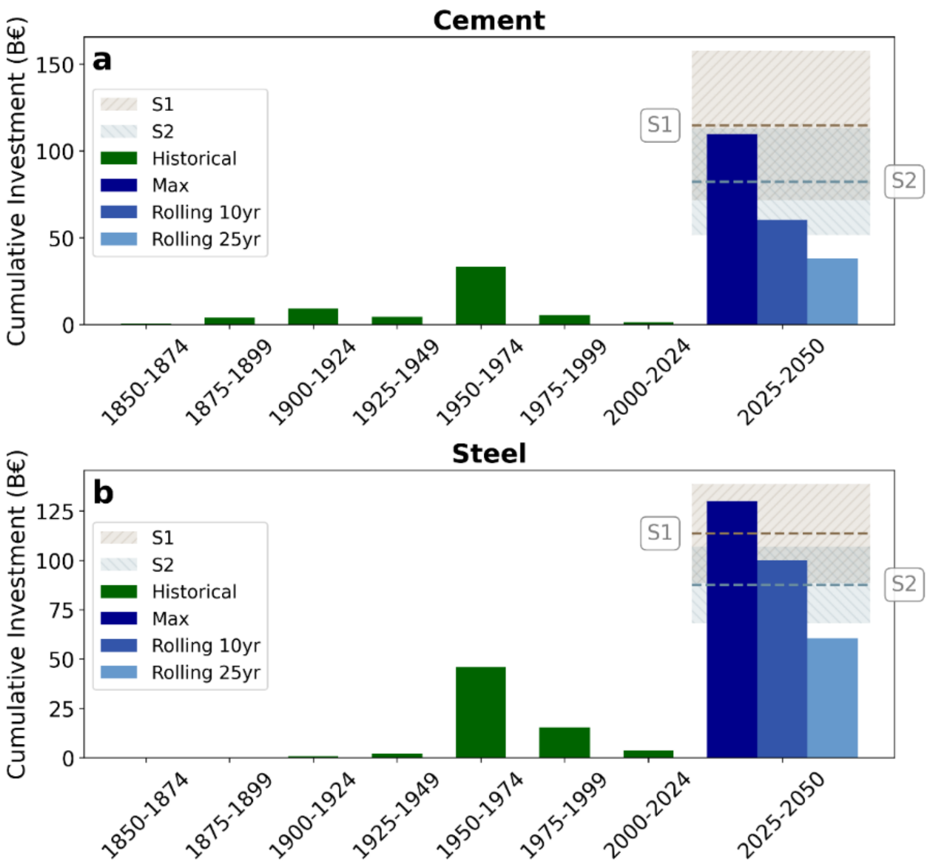

Figure 13. Historical (green) and possible future investments (blue) for cement (**a**) and steel (**b**) for the three investment paces: maximum historical investment (left blue panels); 10-year average (middle blue panels); and 25-year average (right blue panels) of the historical investments. The cumulative investments required to meet near-zero emissions are indicated by the boxes, and the horizontal dashed lines showing the averages for the transformative technology (S1) and the portfolio-based (S2) scenarios.

While the current installed cement clinker capacity is large (282 Mt of clinker), only 168 Mt of cement were actually produced in Year 2017 in the EU, as compared with the 262 Mt produced in Year 2007 (European Commission, n.d.-a). Thus, it should be noted that the investments required to transition the cement industry (in the S1 and S2 scenarios) has in this work been based on the current installed capacity and not current production volumes. Thus, the investments required to transition the cement industry to near-zero emissions by Year 2050 could be reduced if decarbonisation of the entire installed capacity is not required, thereby closing the investment gap.

While informative, historical investment levels do not necessarily constitute an upper boundary to future investments. However, the results indicate that meeting the EU emissions reduction targets would necessitate investment rates in decarbonisation well beyond historical experience, unless the investment needs are reduced through the implementation of less-capital-intensive decarbonisation options or reductions in the material demand.

5.3.1 Financing required – comparing to other estimates

The literature provides several estimates of the magnitude of the financing required to transition from the current materials production system to a low-emissions system. Draghi (2024) has estimated the financing required for the largest energy-intensive industries (chemicals, iron and steel, ceramics, glass, cement, and pulp and paper) at €500 billion for the period of 2025–2040. The European Commission (2024) has estimated the required levels of financing for the period of 2031–2050 as: €100 billion for iron and steel (reduced to €80 billion in a circular economy scenario); €64–67 billion for non-metallic minerals (reduced to €52 billion in a circular economy scenario); and €250–260 billion for chemicals (reduced to €210 in a circular economy scenario). This gives a total of €427 billion for the highest estimates. The results in **Paper V** estimate a financing need of €50–155 billion for cement clinker, €68–140 billion for the steel industry (BF-BOF), and €20–53 billion for steam crackers, for a total of €140–350 billion, depending on the cost assumptions and scenarios applied. Thus, the investment estimate in **Paper V** is lower than other estimates in the literature, as the analysis in **Paper V** focuses on a subset of industrial sectors rather than on the full industrial system.

5.4 Closing the financing gap

The following sections describe pathways for closing the financing gap to transition the materials industries into low-emissions production, as well as putting into perspective the magnitude of the financing required.

5.4.1 Placing into perspective the required financing

While the total of €500 billion for decarbonising heavy industry, as suggested by Draghi (2024), may seem substantial, especially given the analysis in **Paper V** (Figure 13) and the highlighted challenges associated with mobilising this level of capital, it is not obvious as to whether the total is indeed high. To put it into perspective, the total investment of €500 billion corresponds to about 2.8% of the total GDP of the EU in Year 2024 (which was €18,020 billion (Eurostat, n.d.)). The figure can also be compared with investments in defence, agriculture, and artificial intelligence (AI). For example, EU Member States mobilise comparable resources annually for defence purposes. Defence spending reached €343 billion just in Year 2024 and was projected to increase to €381 billion for Year 2025 (European Council, n.d.), whereas the €500 billion required for decarbonising heavy industry refers to the cumulative investment over the period up to Year 2050. Furthermore, the EU's Common Agricultural Policy provides €387 billion in funding for the period of 2021–2027, and agricultural support corresponded to around one-quarter of EU spending in Year 2023 (European Parliament, 2025). Furthermore, it is estimated that €220–294 billion were spent on AI (73% of which was related to private investments) across the EU in Year 2023 (Fonteneau et al., 2025).

As previously mentioned, given the historical patterns of investments in heavy industries, mobilising the capital required to achieve near-zero emissions appears challenging. Nevertheless, the experiences with previous large-scale investment waves in the 1960s and 1980s, combined with the initiatives described above, suggest that mobilising the investments required for industrial decarbonisation is possible. Moreover, such investments are likely to generate spill-over effects throughout the economy through investment multiplier effects, as direct industrial investments induce additional activities along supply chains and in related sectors (Garrison, 1972; Lavopa et al., 2025).

5.4.2 The Value Chain Transition Fund (VCTF)

As previously highlighted, securing private financing for investments in capital-intensive technologies remains a major challenge, while public funding mechanisms are not designed to support the full transition of heavy industry. Thus, in **Paper II**, a novel concept that involves financing investments in capital-intensive technologies and closing the financing gap is presented. The Value Chain Transition Fund (VCTF) is a novel approach to financing the capital-intensive investments that are required to accelerate the transition of industry towards zero-emissions practices. As the VCTF can be used as a private initiative that does not necessarily require governmental involvement, it can be an alternative to closing the gap between available governmental funding and the financing required for the transition. The VCTF builds on the concepts of the supply and value chain and the assumption that it is possible to establish a collective action (see, for example Ostrom (2010)) of the actors along the supply chain while maintaining competitiveness between companies. The rationale for the VCTF is built on three basic 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 dependent upon each other 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-DRI) results in only a marginal effect on the overall cost for the end-consumer (Hörbe Emanuelsson & Johnsson, 2023; Rootzén & Johnsson, 2016b, 2016a; Subraveti et al., 2023).

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 can be designed to be 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 14 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.

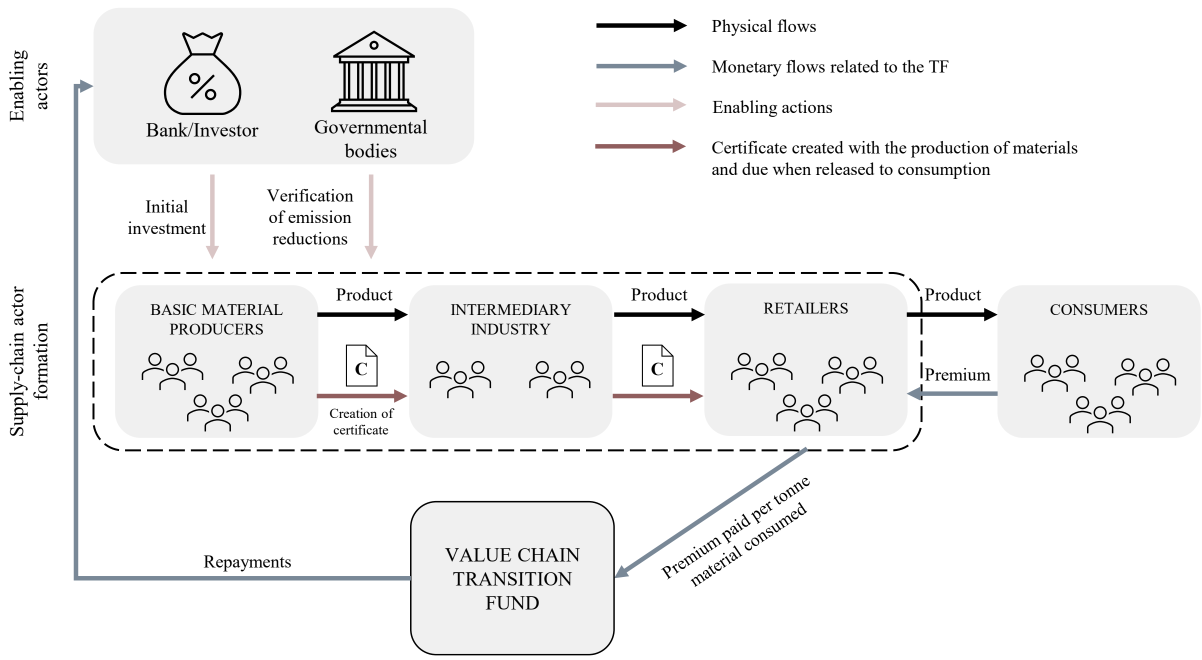

Figure 14. Principal flows and interactions between the actors along the supply chain when the Value Chain Transition Fund (VCTF) is applied.

The following results from **Paper II** explore the application of the VCTF to finance the investments required for CCS and H-DRI to reach near-zero emissions in the EU cement and steel industries. In **Paper II**, the required CCS and H-DRI capacities to achieve near-zero emissions by Year 2050 – and the associated investments – are derived from road maps that include both incremental and transformative (CCS and H-DRI) mitigation options. Figure 15 shows the number of years needed for the VCTF to recoup all the overnight investments in CCS, according to the road maps for the EU cement industry. The bars in Figure 15 correspond to the average estimates of overnight investment needs and operational expenditures. Figure 15a shows that the VCTF can be used to recoup all of the overnight investment needs for CCS in the EU cement sector within 3 years on average. When also including pay-outs for operational expenditures, this time-frame is extended to 6–7 years. Similarly, Figure 15b shows that around 3 years are needed to recoup the overnight investments estimated for H-DRI, while this is extended to 15–16 years when including the operational expenditures. Thus, when considering overnight investment costs alone, the VCTF addresses the financing gap, while the inclusion of operational expenditures further addresses the cost gap between conventional carbon-intensive materials and low-emissions materials.

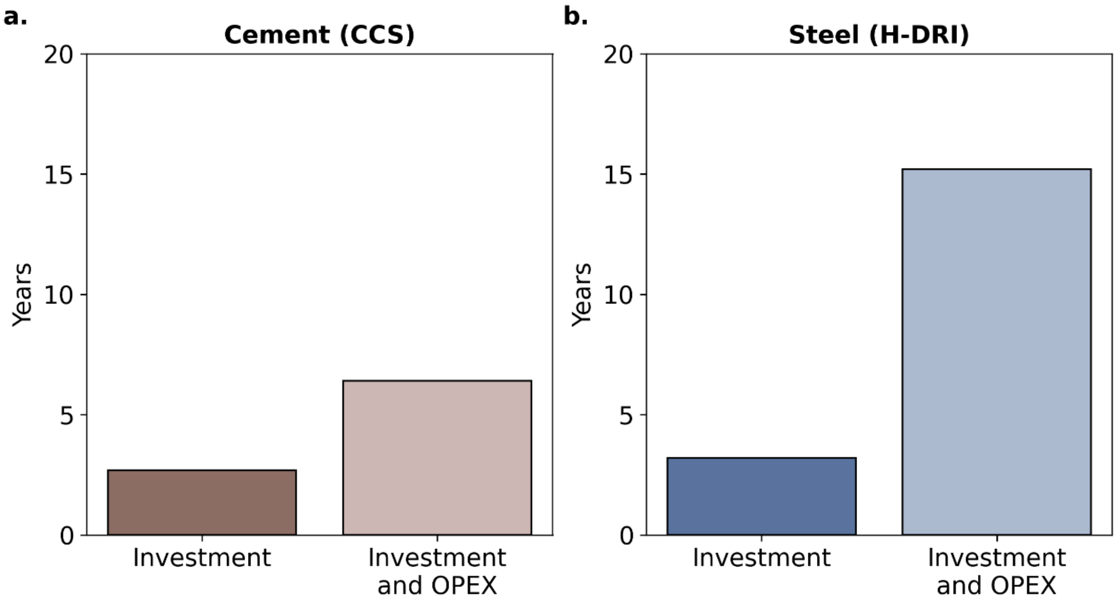

Figure 15. The numbers of years needed to finance the overnight investment and operational expenditures using the Value Chain Transition Fund (VCTF) framework for: **a**) CCS deployment in the EU cement industry; and **b**) H-DRI deployment in the EU steel industry.

CHAPTER 6

Decision-making under uncertainty

The materials transition is highly dependent upon the actions and interactions of multiple actors across the value chain. As previously mentioned, accelerating the transition towards low-emissions production relies on the policy landscape, as stable and stringent climate policies are essential for enabling long-term investments in low-emissions, particularly disruptive, technologies (see, for example Chiappinelli et al., 2021; Nilsson et al., 2021; Phan et al., 2025). However, as previously mentioned, future developments of the EU ETS allowance price remain uncertain. In addition, the deployment of CCS and H-DRI depends on the development of an enabling infrastructure, which includes CO_2 transport and storage networks and sufficient electricity grid capacity and generation. As development of this infrastructure is largely outside the agency of industrial actors, it introduces significant co-ordination dependencies. Uncertainty also surrounds the development of the demand for low-emissions materials, including both the timing of the demand and the extent to which consumers are willing to pay a premium for such materials to close the cost gap. Taken together, these uncertainties require industry actors to make investment decisions under uncertain conditions, such that the profitability of such investments is unclear. At the same time, the actors exhibit different levels of risk tolerance, with some willing to invest under uncertainty, while others are more reluctant to do so. This chapter addresses these aspects.

6.1 Policy, regulation and infrastructure

Paper III analyses CCS deployment dependent on policy push, i.e., an overtime steadily increasing CO_2 price. Figure 16 illustrates the range of emissions reduction pathways for the EU cement industry due to CCS deployment, given different CO_2 price developments (i.e., 'high' and 'low' CO_2 price trajectories in Figure 8) and regulatory conditions (see Table 2). Given the uncertainty surrounding the future development of EU ETS allowance prices, the 'low' and 'high' CO_2 price trajectories result in a wide range of possible transition outcomes. With the high CO_2 price trajectory (meaning a price of around 200 €/tCO_2 in Year 2035), all cement clinker plants adopt CCS by the mid-2030's (as in the Climate scenario in Figure 16).

However, at slower CO_2 price developments (as in the 'low' CO_2 price trajectory), and when considering a lack of CCS-specific regulations, many fewer plants adopt CCS and near-zero emissions are not reached by Year 2050 (see the Combined scenario). In addition, the results include variations in CO_2 price trajectories alongside regulatory and infrastructure conditions, including the availability and costs of CO_2 transport and storage, CCS-specific regulations (such as bilateral agreements governing cross-border CO_2 transport, e.g., whether land-locked countries can transport CO_2 through neighbouring countries), and governmental support for CCS, as outlined in Table 2. The results show the importance of bilateral agreements for CO_2 transport for land-locked countries, as emissions reductions would otherwise decrease from 90% in the Climate scenario to around 80% by mid-century. For more detailed information and analysis, see **Paper III**.

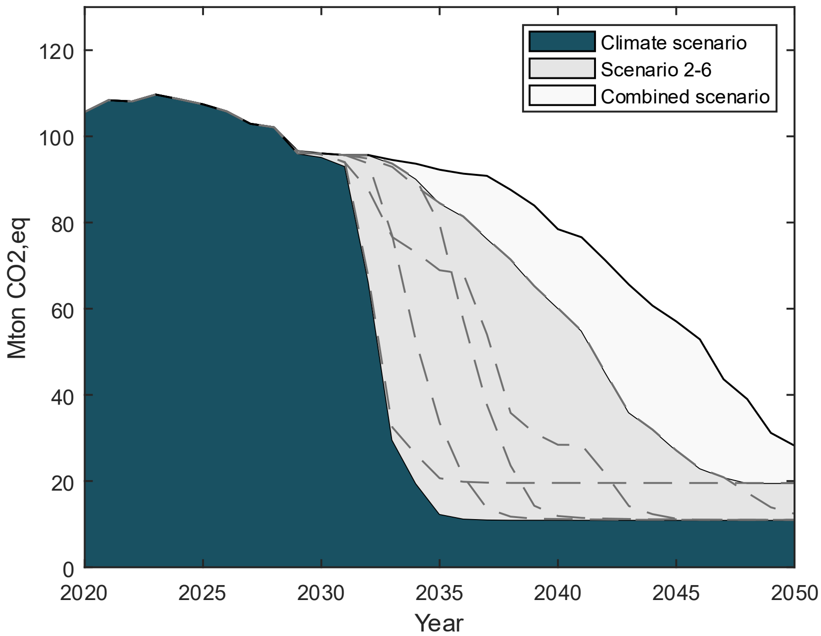

Figure 16. Range of transition pathway outcomes for the cement industry under different CO_2 price trajectories and CCS-specific regulations.

These results point to the fact that the availability of CO_2 transport infrastructure (road, rail, and inland waterways) impacts the abatement cost, and thus the timing with which investments in CO_2 capture technologies become profitable, as well as the importance of the timing of available CO_2 storage infrastructure, including planned capacities and the timeline for their development. However, this analysis assumes that planned infrastructure is realised as expected, without delays or cancellations. In practice, such uncertainties are inherent, so that the future availability of infrastructure remains uncertain. This creates a dependency, or in other words co-ordination barriers, as investments in capital-intensive CO_2 capture technologies are dependent upon the availability of the full CCS value chain. Wesche & Steen (2026) provide empirical evidence from the Porthos project in the port of Rotterdam, showing that such co-ordination barriers can be addressed through a lean governance structure involving state-owned infrastructure firms and a limited group of industrial emitters, enabling more efficient alignment across the CCS value chain.

In addition to the CCS chain, hydrogen-based steel production introduces further logistical complexities. In the case of H-DRI, production can be configured in multiple ways, including on-site hydrogen production that is later used for the production of hot briquetted iron (HBI). Alternatively, hydrogen or HBI may be imported, limiting on-site production to the final steel-making step via EAF. Such configurations introduce additional co-ordination challenges, as they amplify the dependencies between geographically distributed actors and infrastructure systems.

6.2 Industry financial risk tolerance

Producers' levels of risk-aversion impact the levels of certainty that they require to make investment decisions in capital-intensive technologies. The production cost estimates presented in Chapter 4 rely on a constant discount rate to annualize the investment cost. However, the discount rate can be used as a means to illustrate producers' financial tolerance of uncertainty. Producers with higher levels of risk aversion need greater certainty to invest, and since they place less value on future cost savings, they require higher expected returns to justify an investment. Producers with lower levels of risk aversion place greater value on future benefits and are willing to invest under higher levels of uncertainty and for lower expected returns. This is illustrated in the following section through the example of CCS deployment in the cement industry. For more details, refer to **Paper IV**.

Figure 17 shows the CCS adoption probabilities due to policy-push for a range of risk-aversion levels, represented by discount rates that range from 5% (non-risk-averse) to 17% (risk-averse). Figure 17a shows the average CCS adoption probability distributed across risk-level (discount rate) for all the runs. The results show that cement producers with lower discount rates (non-risk-averse actors) consistently adopt CCS to a high degree (90%–97% across runs) than the risk-averse producers. However, as the discount rate increases, CCS adoption becomes less likely. With policy as a driver, the rates of CCS adoption for risk-averse cement producers fall to 79% and 19% as the discount rate increases from 13% to 17%, respectively. Figure 17b shows CCS implementation on a plant level distributed according to the discount rate and CO_2 price in the year of implementation. The results show that plants with higher discount rates (i.e., risk-averse plants) generally require a higher CO_2 price range to justify an investment decision. In many cases, these risk-averse plants do not adopt CCS at all because the CO_2 price does not justify an investment decision. These results highlight that non-risk-averse cement producers are more likely to transition under the ETS alone, as compared with risk-averse producers. In these results, the producers' risk tolerance (discount rate) is randomised between 5% and 17%. However, the actual distribution of producers' risk-aversion levels is unknown, which implies that if actors in general are more risk-averse than modelled, then the transition will be delayed, and the opposite is true if actors are less-risk-averse.

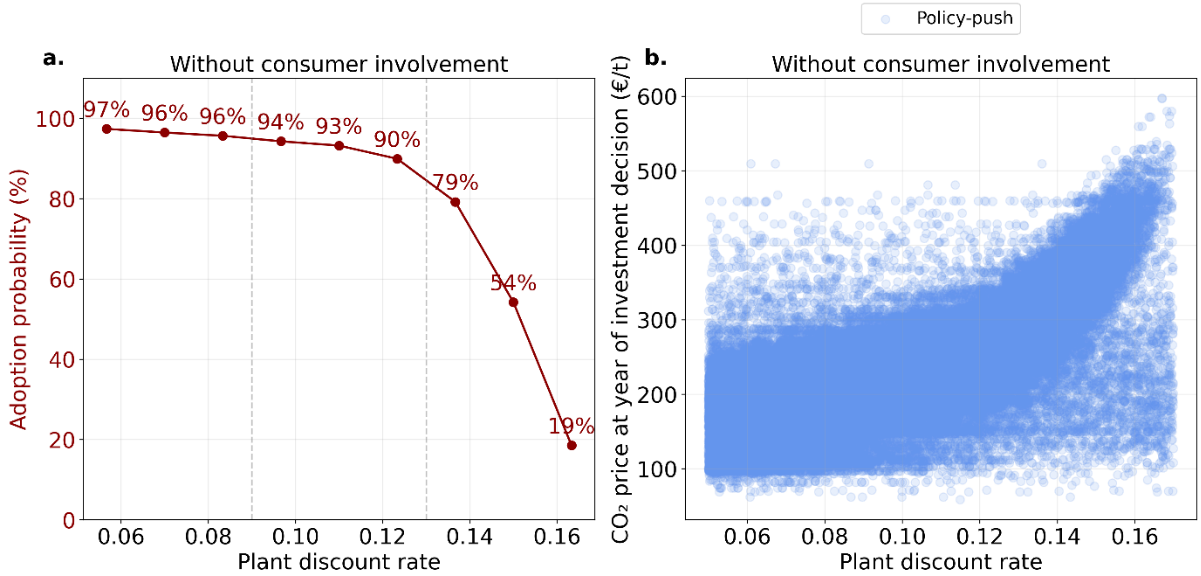

Figure 17. a) CCS adoption probabilities for different levels of risk-aversion (plant discount rates), and **b**) CCS implementation in relation to the plants' discount rates and the CO_2 price in the year of adoption, where each blue dot represents a plant that adopts CCS due to policy push.

6.3 Consumer demand and willingness to pay

Consumers differ with respect to their willingness to pay for low-emissions cement, with some willing to pay a premium for a product that has lower associated emissions but otherwise identical properties (Alberini et al., 2018). Figure 18 shows the probabilities of CCS adoption in the EU cement industry for plants with different levels of risk tolerance, as a result of both policy-push (increasing CO_2 prices) and consumer-pull effects (as compared to Figure 17, which focuses exclusively on policy-push). In a situation where consumers are willing to pay a premium for low-emissions cement, more plants are willing to adopt CCS. The probabilities that risk-averse producers will adopt CCS increase to 92%, 77%, and 51% (Figure 18a), from the corresponding probabilities of 79%, 54%, and 19% without consumer involvement, respectively (Figure 17a). Figure 18b shows that the consumer-pull effect leads to cement producers taking investment decisions across a lower CO_2 price range, corresponding to earlier years. In this scenario, long-term consumer contracts cover 67% of total cement production capacity. With consumer involvement, 28% of all plants adopt CCS at CO_2 prices below €150 per tonne, as compared with only 8% of plants in the absence of consumer involvement.

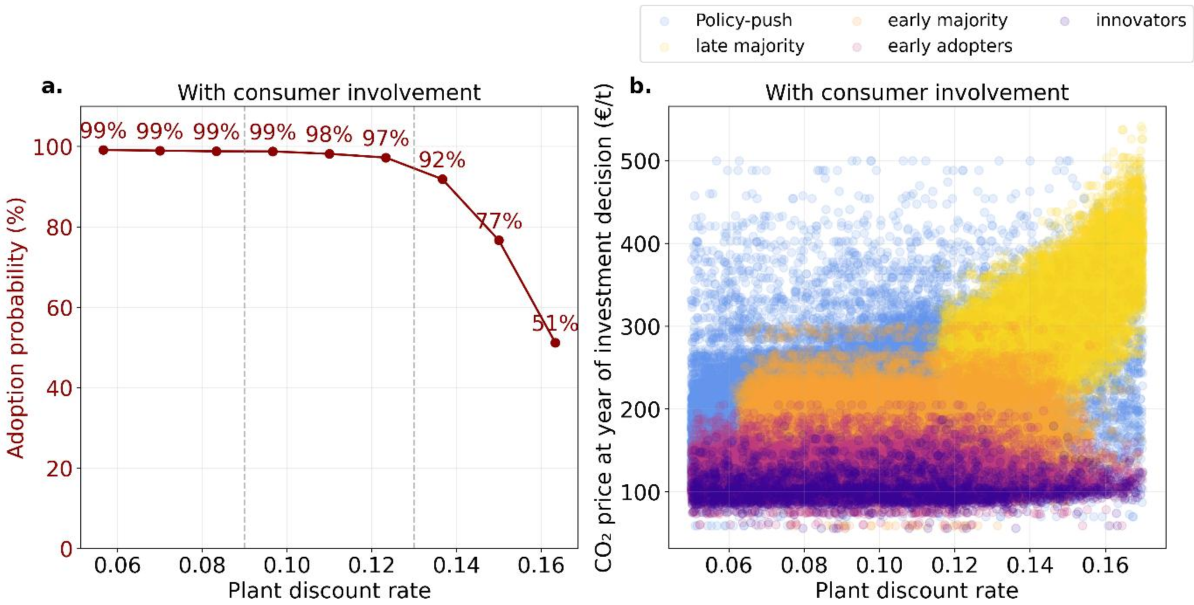

Figure 18. a) CCS adoption probabilities for different levels of risk-aversion (plant discount rates). **b**) CCS implementation in relation to plants' discount rates and the CO_2 price in the year of adoption. Each blue dot represents a plant that is adopting CCS due to the policy-push effect; dots of other colours represent plants that are adopting CCS due to the consumer-pull effect.

This implies that consumers' willingness to pay for low-emissions materials reduces the need for high CO_2 prices to trigger investments in low-emissions technologies and accelerate the transition, suggesting that consumer involvement acts as a hedging mechanism against weaker policy environments. Crucially, this shift benefits not only these companies, since bringing the most-hesitant plants into the transition leads to more-widespread adoption and deep decarbonisation across the industry, thereby allowing Society to progress further, and faster, than would otherwise be possible. On average, the CO_2 price needed to achieve comparable CCS adoption is 60 €/t lower with consumer involvement than when relying solely on policy measures. The results also show that non-risk-averse plant owners are more likely to move first, establishing long-term agreements with innovators and early-adopter consumer segments, while risk-averse plants await higher CO_2 prices and subsequently sign agreements with consumer groups (mainly the early and late majority groups) that have a weaker willingness to pay. While these results show that consumers' willingness to pay for low-emissions materials and products can accelerate the transition, the actual level of willingness to pay for such products is still not well understood. As mentioned previously, there was strong momentum from down-stream actors in the early 2020s, whereby they expressed demand for low-emissions materials. However, the extent to which this is dependent upon macro-economic conditions, as well as the current geopolitical situation and climate policy developments (such as the EU ETS) is not yet clear.

Figure 19 shows the 'perceived' abatement cost curve for all of the modelled plants. The figure illustrates each modelled cement producer's plant-specific assessment of the cost of deploying CCS, including the costs for CO_2 transport and storage. The perceived cost of abatement is calculated based on the producer's level of risk aversion (i.e., discount rate) in the year that the investment decision to deploy CCS was taken. The perceived cost also reflects economies of scale and the extent of learning between projects, i.e., the position of the project along the spectrum from FOAK to NOAK. This results in a wide range of plant-level abatement costs, ranging from €100 to €300 per tonne of CO_2. From Figure 19, it is clear that plants with lower abatement costs manage to transition in response to the CO_2 price (blue bars), while plants with higher abatement cost assessments benefit and transition due to consumer involvement (green bars). However, the plants located furthest to the right reflect FOAK rather than NOAK costs, implying that consumers bear the higher costs associated with first-of-a-kind projects. As such, consumers play a key role in enabling the deployment of these initially more expensive projects and in incentivising early adoption of CCS by producers.

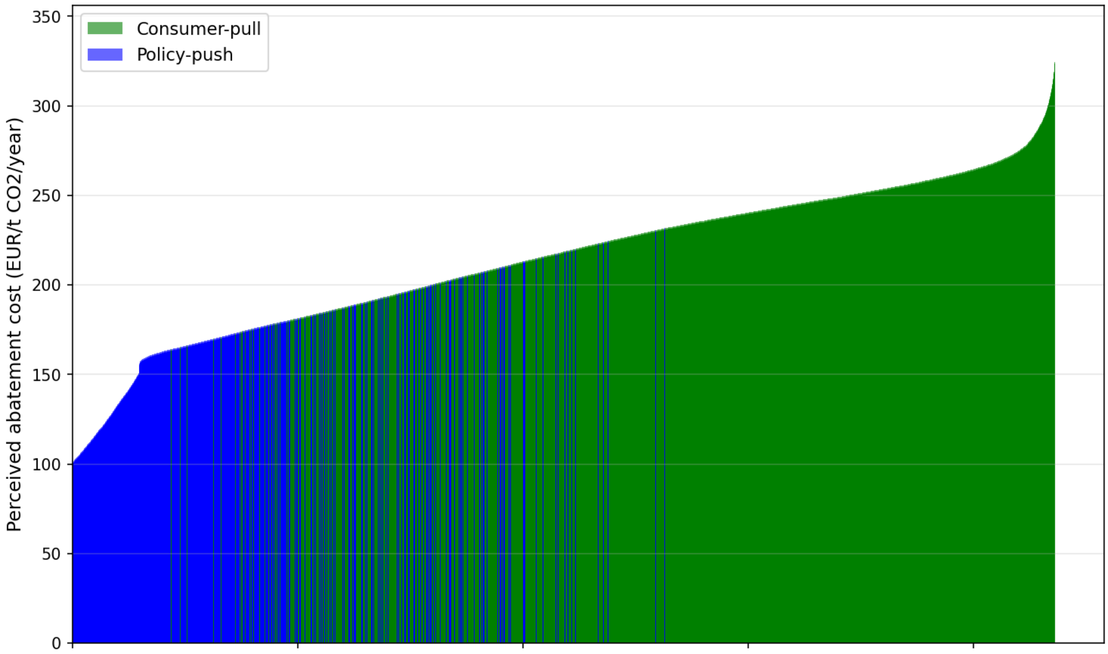

Figure 19. Perceived Marginal Abatement Cost curve showing the 'perceived' plant-level cost for adopting CCS, including the cost for transporting and storing CO_2, for each simulated plant. The term 'perceived' here refers to each plant evaluating the cost for CCS according to their risk tolerance level (discount rate). The cost shown is also dependent on economies of scale and learning between projects (i.e., FOAK or NOAK costs). The blue bars indicate plants that adopt CCS in response to the CO_2 price alone, and the green bars indicate plants that adopt CCS in response to consumer involvement.

Connecting back to the cost gap between emissions-intensive production and low-emissions production, the results in Figure 19 indicate that this gap varies significantly across producers. This variation is driven in part by differences in CCS deployment costs, including CAPEX differences that are attributed to economies of scale. However, other factors, that are not included in these results, also contribute to differences between producers, such as OPEX variations associated with CO_2 transport and storage, which depends on plant location, including proximity to harbours and suitable storage sites.

6.4 Paying for the materials transition

Since First-of-a-kind, low-emissions projects have higher transition costs than Nth-of-a-kind projects, and since both forms generally involve higher production costs than conventional materials production, a central issue is who should bear these additional costs. A common argument is that industry should bear the costs of decarbonisation, consistent with the Polluter Pays Principle. However, in practice, industry is often reluctant to absorb fully these costs due to investment and market barriers. As discussed previously, capital-intensive decarbonisation projects are associated with substantial risks and uncertain future profitability, which makes it challenging to mobilise private investments. As a result, State support and public guarantees play crucial roles in enabling such investments and in de-risking these projects for private actors (Dolphin et al., 2023; Zetterberg et al., 2021).

When public support is financed through taxation, the costs of decarbonisation are effectively distributed across Society. In such a case, Society takes on the investment risk. This raises broader questions related to fairness and whether responsibility for the cost of decarbonisation should be assumed primarily by producers, passed on to consumers through higher prices, or shared collectively through public funding mechanisms. In reality, there are no clear boundaries between these options. Even when the costs are initially absorbed by industry, they are likely to be passed on to consumers through higher prices for materials and products, with the cost increase ultimately being borne by the consumers using the materials. However, even relatively small cost increases at the level of final products may have important implications for competitiveness, as they can reduce producers' ability to compete with lower-cost alternatives, particularly in internationally exposed markets, such as the steel industry, which ultimately affects the profitability of low-emissions production. At the same time, achieving near-zero emissions requires the deployment of technologies across producers with widely differing transition costs, capabilities, and other constraints. Some emissions sources will, as a consequence, be significantly more expensive to abate than others.

From a system perspective, reaching near-zero emissions is unlikely to be achieved by focusing exclusively on the lowest-cost abatement options. Instead, it requires a broader societal willingness to absorb the cost-heterogeneity across producers. This may involve consumers accepting price premiums for low-emissions materials, alongside public mechanisms that support high-cost but necessary transitions. However, the extent to which such willingness exists, and how it may evolve over time, remains uncertain. Even in cases where large, publicly governed buyers are expected to play a leading role due to their alignment with national climate targets, it is not yet clear to what extent they are willing or able to absorb higher costs for low-emissions materials in practice. In this context, Society not only benefits from the availability of low-emissions materials, but also plays a key role in enabling their deployment by sharing both the associated costs and risks.

CHAPTER 7

Summary and conclusions

Deploying capital-intensive technologies, such as CCS and H-DRI in the cement and steel industries, presents unique challenges. These technologies require substantial up-front investments that are challenging to finance through conventional channels, while their site-specificity limits opportunities for learning between projects and cost reductions over time. As a result, materials production costs for low-emissions materials will be higher compared to their carbon-intensive counterparts, due to higher capital and operational expenditures. In addition, the results from this work indicate that the order of magnitude of investments required to transition the EU cement and steel industries to near-zero emissions in the coming 25 years far exceeds that of the investments previously made in these industries. Deployment of these technologies is also dependent upon co-ordination between several actors, as they are reliant on sufficient grid capacity, the availability of a transportation infrastructure, and adequate CO_2 storage capacity.

The EU ETS is the most-important policy instrument to address the cost gap between the production of low-emissions material and their emissions-intensive counterparts. As the cap on total emissions declines and the free allocation of emissions allowances is phased out, the cost gap is intended to decrease. However, the timing and magnitude of the development of the EU ETS allowance price are uncertain, especially due to current geopolitical instabilities and increasing energy prices, which have resulted in some EU Member States pushing to ease the stringency of the EU ETS.

While the production costs of low-emissions materials are significantly higher than those of conventional emissions-intensive alternatives (194% for cement and 50% for steel), this work shows that the impact is substantially reduced when costs are passed down-stream along the value chain. At the level of end-use applications, the resulting cost increase is relatively small (1% for a high-speed railway, and 1% for a passenger electric vehicle). Expanding the system boundary from the plant level to a value chain perspective, therefore, provides a more-comprehensive understanding of the economic implications of industrial decarbonisation. At the same time, this work demonstrates that deep decarbonisation can be achieved along the value chain at these relatively small increases in cost, with emissions reduced by 35% and 46% for the case for the high-speed railway and passenger electric vehicle, respectively.

Currently, there are insufficient policy incentives for most producers of basic materials across the EU to invest in low-emissions technologies. Therefore, it is argued in this thesis that it is important and logical that the actors along the supply chain for emissions-intensive materials, such as cement and steel, should become actively involved in incentivising and sharing the costs associated with implementing transformative technologies, such as CCS and H-DRI. The actors involved in the cement and steel supply chains could play central roles in the transition process by sharing the risks associated with investing in high-cost abatement measures. Building on the principle of distributing cost increases throughout the value chain, this work proposes a novel mechanism to address the financing challenge and close the financing gap: the Value Chain Transition Fund (VCTF), which leverages down-stream cost pass-through to consumers in order to create new financing opportunities. The VCTF aims to overcome market barriers and address the challenges associated with securing financing for investments in capital-intensive technologies. This work shows that by applying a VCTF premium to end-products that: 1) all of the overnight investments needed for CCS in the EU cement industry can be recouped in under 3 years on average; and 2) the overnight investments needed for hydrogen-based steel-making in the EU steel industry can be secured on average within 3 years.

Although this work shows that the investments required to achieve near-zero emissions in the cement and steel industries over the next 25 years far exceed those of any previous historical period, the EU has demonstrated the ability to mobilise capital of similar magnitudes, as evidenced by investments in defence, agricultural subsidies, and artificial intelligence.

This work further examines the transition outcomes under conditions of uncertainty, emphasising the roles of actors in shaping the transition. As noted earlier, a strong and stable long-term policy framework is crucial to incentivising change, as it provides predictability in relation to the future profitability of the large-scale investments needed to achieve near-zero emissions by mid-century. However, decisions regarding investments in CCS and H-DRI ultimately lie with plant owners, which means that, industry actors' willingness to invest, and their levels of risk tolerance become critical aspects of the transition. Industry actors have heterogeneous strategic behaviours that are shaped by differences in risk tolerance, with some acting as front-runners, meaning that they are willing to invest under uncertain policy developments and profitability conditions, while others delay investment until sufficiently incentivising policy frameworks are in place, thereby influencing the pace of the transition.

Apart from policy acting as a push factor for industrial transition, consumers' willingness to pay and demands for low-emissions materials exert a pull factor that further drives the transition, since industry actors can secure a profitable outlet for low-emissions materials. This work shows that consumers' willingness to pay for low-emissions materials plays an important role in accelerating the transition, in addition to policies. The consumer-pull effect is particularly beneficial for risk-averse cement producers, as it encourages earlier CCS adoption (43% of plants adopting CCS by Year 2035, as compared with 18% without consumer involvement), increases the share of plants that undergo transition, as compared to relying exclusively on policy (84% versus 72% of plants adopting CCS), and provides a form of hedging that partially offsets the uncertainty inherent to weak policy environments. Long-term contracts enhance this effect by providing price and demand stability, enabling risk-averse plants to invest in CCS sooner than they might otherwise would. While a strong CO_2 price remains essential, since a consumer-pull strategy cannot drive the transition on its own, the combination of policy-push and consumer demand proves to be far more effective than either mechanism applied in isolation.

7.1 Recommendations for future research directions

The transition of industry to net-zero emissions is complex, and while this thesis provides important insights, several future research directions emerge. Importantly, this work is limited to the materials transition within the EU and adopts a set of limitations which abstract from several aspects that are likely to be critical in practice. In particular, the global nature of industrial markets and the heterogeneity across sectors are not explicitly represented. For instance, cement production is largely characterised by regional markets due to high transport costs in comparison to the value of the product, whereas steel is traded globally, which raises fundamental questions regarding the geographical location of production in relation to competitiveness, and the potential for emissions leakage through imports of intermediate products such as HBI and end-products.

Furthermore, this work does not explicitly account for demand-side dynamics or market formation. The transition to low-emissions materials ultimately depends not only on technological feasibility and producers' willingness to adopt these technologies, but also on the existence of sufficient demand and willingness to pay for higher-cost products. Even marginal cost increases may challenge market uptake if down-stream actors are unwilling or unable to absorb these costs. Future research could therefore adopt a more integrated perspective that considers market development, profitability constraints, and policy mechanisms required to support both supply- and demand-side transitions, in order to better understand the implications of industrial decarbonisation. Some other more-specific research directions are listed below.

First-mover advantage: Since the transition ultimately depends on the investment decisions made by the producers of materials, some actors will need to move first. It is, therefore, of importance to analyse the advantages and disadvantages of being a first-mover, and to assess whether the potential benefits outweigh the inherent risks.

The impacts of policy measures on the different stages of technological development: Building on the findings of this thesis, further research is needed to examine how policy can effectively support the transition from the pilot and demonstration phases to full-scale deployment of CCS and H-DRI. In particular, it could be investigated how different policy instruments align with the different stages of technological maturity, including how funding and financing mechanisms evolve along this trajectory and where critical gaps remain.

Integrating technological transition dynamics into transition modelling: Future studies could incorporate S-curve dynamics and growth perspectives into transition modelling, to capture more effectively the non-linear development of low-emissions technologies. Linking these dynamics to policy design and investment behaviour would improve our understanding of how technologies progress through the pilot, demonstration, and commercialisation phases.

Industry risk behaviours and consumers' willingness to pay: This entails studying the interplay between industry risk behaviours and consumers' willingness to pay in shaping the transition dynamics. In particular, more-detailed empirical studies, for example based on interviews with consumers, could provide further insights into how consumers value low-emissions materials and the nature and extent of their willingness to pay for such products. Similarly, it would be of interest to analyse industrial risk behaviours in greater detail, including how they are influenced by the evolving political landscape. This would answer questions regarding the extent to which consumer demand can mitigate policy-related risks, as well as what additional conditions, beyond a predictable policy environment, are required for industry actors to undertake large-scale, capital-intensive investments.

Circularity to decrease the demand for primary materials: This involves studying the potential of circularity measures to reduce the demand for primary materials. Lowering the demand would not only decrease emissions from materials production, but would also reduce the need for resource extraction. In addition, a decline in the primary materials demand would likely lessen reliance on capital-intensive mitigation options. This, in turn, could reduce the scale of up-front investment required for the transition. As highlighted in this thesis, meeting the investment needs associated with transitioning the current levels of primary materials demand to near-zero emissions represent a challenge, and increased circularity may present a valuable way to address this challenge.

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