Delft University of Technology

Master Thesis

A Decision-Support Framework for Carbon Capture Investment and Global Cement Distribution under the Influence of Emerging Carbon Pricing Policies

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Abstract

This thesis examines the integration of carbon-reducing technologies and distribution decisions within the cement industry's supply chain, with a focus on the impact of these decisions on emerging carbon pricing mechanisms, particularly the European Union's Carbon Border Adjustment Mechanism (CBAM). As the cement industry is a major contributor to global carbon emissions, there is significant pressure to reduce its environmental footprint. Despite the potential of carbon capture technology, its adoption within the cement industry has been slow and remains limited. Moreover, decision-support tools to guide these decarbonisation decisions remain scarce. This thesis develops and validates an integrated framework that combines long-term demand forecasting, strategic investment in carbon capture technologies, and distribution planning under evolving carbon-pricing regimes.

First, an extensive data collection process assembles detailed information on global cement production facilities, bilateral trade flows, and regional emission factors, providing a robust empirical foundation for the analysis. A country-level consumption series for 1995–2023 is then reconstructed by combining historical trade flows with production capacity data, applying outlier detection and interpolation techniques to ensure trend consistency. Building on this foundation, a systematic forecasting exercise produces reliable country-level demand – which is thereafter distributed over the three biggest populated cities in the country – projections for 2025–2050, which are spatially disaggregated to define demand nodes for the optimisation model.

The core of the methodology is a Mixed-Integer Linear Programming (MILP) model that simultaneously optimises binary investment decisions in carbon capture retrofits and continuous cement flows across a 25-year planning horizon. The model's objective function maximises profit by balancing expected revenues against production, transportation, emissions-related costs, storage and transportation costs for captured carbon, and capital expenditures for retrofit investments.

To evaluate model robustness and the influence of future policy environments, the study conducts comprehensive parameter sensitivity and scenario analyses. Sensitivity analysis systematically perturbs key input parameters – such as production and transportation costs – to identify which uncertainties most affect optimal investment and distribution strategies. Scenario analysis contrasts three carbon pricing pathways (STEPS, APS, and NZE), each evaluated with and without the CBAM, to investigate how different policy trajectories shape investment decisions and trade flows.

Results show that the CBAM consistently accelerates retrofitting investments and reshapes international cement trade flows across the STEPS and NZE carbon pricing pathways. Under more aggressive carbon pricing scenarios (APS and NZE), domestic European retrofit projects become viable even without the CBAM, although the mechanism continues to redirect marginal investments toward lower-cost regions. Sensitivity tests reveal that assumptions about regional production costs exert the strongest influence on investment outcomes, while variations in transport-related costs have comparatively limited effects.

This thesis makes three key contributions. Methodologically, it provides a validated, end-to-end decision-support framework that integrates comprehensive data preparation, long-term demand forecasting, mathematical optimisation, and detailed post-analysis. Empirically, it offers novel insights into how the CBAM implementation and alternative carbon pricing trajectories jointly determine the geography of carbon capture investments and global cement flows. Practically, it delivers a strategic tool enabling industry stakeholders and policymakers to plan effective long-term decarbonisation strategies under uncertainty, highlighting the importance of targeted support measures in higher-cost regions and the need to align regulatory designs with the economic realities of global supply chains.

Preface

When I began my master's thesis, I knew I wanted to make a meaningful contribution by tackling complex challenges and supporting the broader goal of sustainability. After completing a network optimisation course during my master's program at the TU Delft, it didn't take me long to decide that I wanted to work at the intersection of network optimisation and supply chain decarbonisation.

Therefore, I am proud to share with you my thesis, *A Decision-Support Framework for Carbon Capture Investment and Global Cement Distribution under the Influence of Emerging Carbon Pricing Policies*, as it represents my endeavour to bridge rigorous academic methods with real-world sustainability imperatives.

I am grateful to KPMG for granting me the opportunity to conduct this research within their Advisory Supply Chain & Procurement team. I extend my sincere gratitude to Mike Kelly and Philippe Clercx: their incisive feedback, thoughtful questions, and support have elevated the quality and practical relevance of my work.

My deepest appreciation goes to my university supervisors, Patrick Stokkink and Arjan van Binsbergen. Throughout the project, I have gained invaluable insights and steadfast encouragement, which have greatly supported my focus and confidence. I have also benefited immensely from their academic expertise, and their rigorous feedback and fresh perspectives have challenged me to refine my assumptions and enhance the research quality. Their unique combined mentorship was instrumental in navigating me through the complexities of this project.

I also owe a profound debt of gratitude to my family and friends for their unwavering support. These fantastic individuals have supported me throughout my journey and made significant contributions to the successful completion of my thesis.

Beyond the technical knowledge acquired, this research has refined my project management, analytical, and communication skills.

As I conclude this chapter, I hope that my findings will offer value to both the academic community and KPMG. This entire experience has contributed significantly to my professional and personal growth and will serve as a solid foundation for my future career.

Robin Karthaus

July 9, 2025

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List of Abbreviations

AB Agent-Based. 23

APS Announced Pledges. 16

CBAM Carbon Border Adjustment Mechanism. 10

CCS Carbon Capture and Storage. 22

CCU Carbon Capture and Utilisation. 25

EU ETS European Union Emissions Trading System. 10

IEA International Energy Agency. 34

IQR Interquartile Range. 15, 37

LCA Life-Cycle Assessment. 23

MAPE Mean Absolute Percentage Error. 15, 38

MCDM Multi-Criteria Decision Making. 23

MILP Mixed-Integer Linear Programming. 11

NZE Net Zero Emissions by 2050. 16

OPC Ordinary Portland Cement. 20

SD System-Dynamics. 23

STEPS Stated Policies. 16

TP Transportation Problem. 27

UK United Kingdom. 19

Chapter 1

Introduction

The cement industry stands at a pivotal crossroads, where strategic optimisation and investment in carbon-reducing technologies can shape its long-term sustainability and compliance with evolving regulations. As the second most consumed material globally (Goggins, 2024), cement's environmental impact is becoming increasingly pressing – particularly as demand continues to rise, especially in developing regions undergoing rapid urbanisation and infrastructure expansion (Hasanbeigi & Sibal, 2024). Cement manufacturing is responsible for an estimated 6–8% of global carbon emissions (Cadavid-Giraldo et al., 2020; Ige et al., 2024; P. Wang & Papadokonstantakis, 2024).

Reducing emissions in this sector is therefore critical. However, alternative low-carbon cement types and efficiency improvements alone are unlikely to meet long-term climate targets (Hills et al., 2016). A significant portion of the carbon emitted during cement production originates from the calcination process, which is crucial for producing clinker, a primary component of cement (Antzaras et al., 2023). As a result, carbon capture technologies are increasingly viewed as essential to the industry's decarbonisation pathway (Biniek et al., 2024). Despite this recognition, the literature remains limited, especially concerning decision-making tools designed to support industry leaders in formulating effective decarbonisation investment strategies.

At the same time, the policy landscape is evolving. Around the world, various carbon pricing mechanisms, such as Canada's Output-Based Pricing System (Government of Canada, 2025), are either already in place or being announced, aiming to reduce emissions by placing a cost on carbon. Another example is the European Union's Carbon Border Adjustment Mechanism (CBAM), which has been introduced to complement the European Union Emissions Trading System (EU ETS) (European Commission, 2024b). The EU ETS is a cap-and-trade system where companies are required to purchase allowances for each ton of carbon they emit (European Commission, n.d.). The goal of the EU ETS is to incentivise industries to reduce emissions by making it more expensive to pollute. While this system encourages domestic reductions, there is a concern that it could lead to "carbon leakage" – the relocation of emissions-intensive production to regions with laxer or no regulations or consumers switching to other products where lesser or no carbon price is levied (Hayes et al., 2024). To address this, the CBAM imposes a carbon price on imported goods, ensuring that foreign producers pay for their emissions just as EU-based companies do. These pricing mechanisms aim to incentivise decarbonisation in carbon-intensive industries, such as cement, ensuring that climate goals are met.

The introduction of the CBAM complicates global supply chains, disrupting traditional trade dynamics and forcing industries such as the cement industry to navigate these new rules. The uncertainty around the future of carbon pricing mechanisms adds further complexity to the cement industry's decision-making processes. This creates a pressing need for the industry to make strategic investment decisions that will support both regulatory compliance and long-term sustainability.

This thesis explores how cement producers can strategically respond to these evolving regulatory conditions. Producers have several potential strategies available, including the use of alternative fuels or raw materials and reallocating shipments to different markets. This study specifically focuses on plant-level investments in carbon capture technologies, employing an integrated decision-making framework that simultaneously addresses strategic decarbonisation investments and global cement distribution flows. Central to this analysis is the impact of the CBAM, which shapes both investment incentives and international trade patterns. By evaluating scenarios with and without the CBAM implementation, this research provides valuable insights for industry practitioners and policymakers navigating complex regulatory landscapes.

1.1 Problem Statement and Research Approach

Existing decision-support models for the cement industry typically treat strategic investment and distribution decisions as separate problems. The advent of the CBAM, however, creates a tightly coupled decision environment in which investment choices and distribution flows interact under variable, location-dependent carbon costs.

Accurate long-term demand projections are fundamental to capturing these interactions. Historical trade and capacity data are utilised to reconstruct country-level consumption, with outlier detection and interpolation ensuring consistency of the trend. A rigorous forecasting framework then produces country-level demand estimates for 2025–2050. These forecasts feed into the optimisation model's demand nodes.

To address the integrated problem, a Mixed-Integer Linear Programming (MILP) formulation has been developed that simultaneously optimises binary investment decisions in carbon capture technologies and continuous distribution flows over a 25-year planning horizon. The MILP approach was selected for its ability to identify globally optimal solutions to complex decision problems involving discrete and continuous variables – an essential feature for accurately evaluating optimal strategic investments alongside distribution decisions. While alternative modelling approaches can capture additional system realism, they often sacrifice the guarantee of optimality, which is critical for supporting robust and reliable decision-making. The objective function balances revenues against production, transport, emissions, CBAM levies, storage, and investment costs.

Robust parameter tuning and sensitivity testing constitute a substantial component of the methodological pipeline. Key cost parameters are varied individually to identify drivers of retrofit decisions and trade-flow shifts. Scenario analysis then evaluates three distinct carbon pricing trajectories, each with and without the CBAM regulation activated. This integrated approach demonstrates how cost assumptions, policy design, and carbon cost uncertainties collectively influence the identification of optimal decarbonisation pathways.

Taken together, these methodological steps form a cohesive framework for evaluating investment and distribution strategies under emerging carbon pricing regimes. This pipeline not only addresses a gap in the cement industry literature regarding the impacts of the CBAM and evolving carbon mechanisms but also delivers a decision-support tool that stakeholders and policymakers can apply themselves to explore the combined effects of carbon regulations and supply chain dynamics under changing input parameters or future policy scenarios.

1.2 Research Questions

The following primary and secondary research questions have been designed to guide this study, focusing on the optimisation of cement flow and investment decisions within supply networks under the CBAM policy framework:

RQ: How does the Carbon Border Adjustment Mechanism impact the optimisation of strategic investment in carbon capture production technologies and cement distribution within global supply chains?

SQ1: What are the primary cost and emissions drivers affecting decisions on cement flow and green technology investments?

SQ2: What data and parameters are required to develop a mathematical model that integrates the CBAM costs, cement flow, and technology investments?

SQ3: How can a mathematical optimisation model be developed to integrate cement flow and investment decisions in carbon capture technologies while accounting for the CBAM-related costs?

SQ4: How do alternative carbon price trajectories modulate the effects of the CBAM on investment and supply chain decisions in the cement sector?

SQ5: What insights and recommendations can be gained from applying the model to a case study?

1.3 Reading Guide

This thesis unfolds across nine chapters, each complemented by detailed appendices. Following this introductory chapter, chapter 2 presents an extensive discussion of the methodological framework employed in the research. chapter 3 establishes the theoretical foundation, reviewing key concepts and prior studies that inform the investigation. In chapter 4, the focus turns to compiling the necessary input data – ranging from plant-level parameters to transportation costs and carbon capture technology estimates – that underpin the mathematical model. Building on these inputs, chapter 5 reconstructs historical cement consumption patterns and projects future demand at the national level. The core methodological contribution is detailed in chapter 6, where a mathematical optimisation model integrates distribution decisions with carbon capture investment strategies. Outcomes under alternative policy scenarios are then explored in chapter 7, which presents the main findings alongside sensitivity analyses. Finally, chapter 8 summarises the study's key contributions and implications, while chapter 9 reflects on limitations and outlines directions for future research.

Chapter 2

Methodology

This chapter outlines the methodologies used to address the research questions concerning the optimisation of strategic investment and distribution decisions in the cement industry's supply chain. Specifically, the research aims to analyse the impacts of carbon-reducing technologies and the CBAM on cement production and distribution. The methodological framework presented here includes the steps involved in literature review, data collection, forecasting, mathematical modelling, sensitivity analysis, and scenario analysis.

The primary approach used in this study is quantitative, leveraging a MILP model to optimise decisions regarding cement plant investments and distribution. The use of MILP techniques is essential when an optimisation problem involves both binary or integer variables alongside continuous variables (Fachrizal et al., 2020). Demand forecasting, along with extensive data collection and processing, is integral to the development of the model.

This chapter provides a summary of the methodologies applied and explains how each contributes to addressing the secondary research questions, which collectively support answering the primary research question of the thesis. The graphical representation included in this chapter (Figure 2.1) illustrates the methodological flow, the research questions addressed by each step, and the relationships between the different components, providing a clear overview of the overall research process.

2.1 Methodological Choices

This section outlines the sequence of methodological steps employed to address the research questions posed in the thesis. A graphical overview of the research workflow with the applied methodologies is presented in Figure 2.1, illustrating how each method (indicated by the purple boxes) interacts with the data inputs (shown in the oval boxes) and connects to the subsequent stages of analysis. The methodology boxes also indicate the secondary research questions they are intended to address.

The first phase establishes the theoretical and contextual basis through a structured literature review. Two distinct chapters emerge from this phase: one focused on theoretical background (chapter 3) and another on data collection (chapter 4). The literature review integral to these chapters not only synthesises existing knowledge on cement production, supply chain decision-making, carbon-capture technologies, and regulatory mechanisms such as the CBAM but also extracts quantitative parameters – transportation costs, emission intensities, carbon-price trajectories, and geographic data – that feed directly into the optimisation model.

A dedicated forecasting methodology addresses the lack of reliable long-term demand projections (chapter 5). Historical trade, industry production utilisation factor, and capacities identified during data collection serve as inputs to generate country-level cement demand estimates for 2025–2050. These projections define the demand nodes within the MILP framework.

The core optimisation model is formulated as an MILP in chapter 6. Demand forecasts and collected

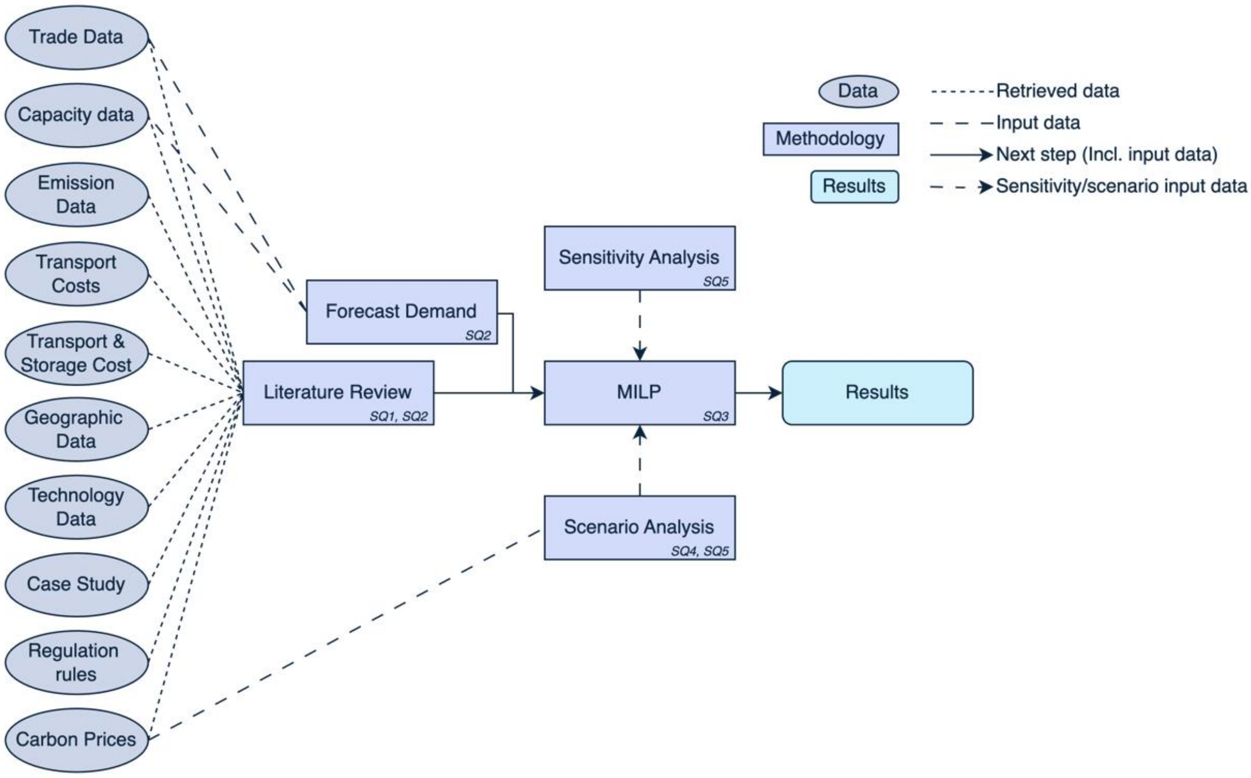

Figure 2.1: Workflow diagram of the study's methodological sequence, showing how literature review, data collection, forecasting, mathematical modelling, and sensitivity & scenario analyses interconnect.

data are integrated to determine optimal investment in carbon-capture technologies (binary decisions) and the distribution of cement shipments (continuous decisions) over a 25-year horizon. The objective function maximises profit.

Robustness of the optimisation results is tested in chapter 7 through two complementary analyses:

- **Sensitivity analysis:** Key parameters are varied one at a time to identify which inputs most strongly influence the model's output.
- **Scenario analysis:** Three carbon-pricing pathways are each evaluated with and without the CBAM. Six model runs reveal how policy stringency and the border adjustment levy reshape investment and distribution decisions.

The following subsections will discuss each methodology in detail, beginning with the literature review, proceeding to forecasting and the core modelling process, and concluding with sensitivity and scenario analyses.

2.1.1 Literature Review

The first step in the research process involves conducting a comprehensive literature review, which serves both as a data-gathering method and as a means to establish the theoretical and contextual foundation of the study. This methodology draws on a wide range of sources, including peer-reviewed scientific literature, industry reports, official legislative sources, and insights from consultancy and international policy institutions, to collect relevant knowledge and quantitative data related to cement production, supply chain decision-making, carbon reduction technologies, and regulatory frameworks such as the CBAM.

This methodological step is critical because it addresses two key needs in the research: first, to understand the current state of the field and identify the primary cost and emissions drivers affecting the investment and distribution decisions (sub-question 1), and second, to gather the essential input data required for the optimisation model (sub-question 2). These data include, among others, transport costs, emission intensities, carbon prices, and the geographic characteristics of suppliers and customers.

Given the dual purpose of the literature review, the findings are presented across two chapters. The first chapter, titled "Theoretical Background" (chapter 3), focuses on developing a theoretical and contextual understanding of the cement industry's environmental impact, carbon pricing mechanisms, and relevant decarbonisation technologies. This chapter primarily contributes to answering sub-question 1. The second chapter, "Data Collection" (chapter 4), applies the literature review methodology more specifically to identify and extract the data required to populate the optimisation model. This includes explaining assumptions and resolving data gaps, addressing sub-question 2.

During the data collection phase, it became clear that a key input – reliable long-term forecasts of global cement demand – was not readily available in the literature or existing databases. This limitation could not be resolved solely by the literature review methodology. As a result, a separate forecasting methodology was introduced, detailed in chapter 5. The forecasting chapter builds on the foundation established through the data collection process and completes the answer to sub-question 2, which will be discussed in the following subsection.

2.1.2 Forecasting

Long-term country-level cement demand series are not readily available in the literature (see chapter 4), so historical consumption is first reconstructed for 1995–2023. Total imports and exports from the *BACI Bilateral Trade Flows Dataset* are combined with production capacity figures from the *SFI Global Cement Database*, while applying a 75% utilisation rate to estimate the annual consumption (Jaganmohan, 2024). Outliers in each national time series are detected via both Z-score and Interquartile Range (IQR) methods and replaced by linear interpolation, ensuring consistency in underlying trends.

After comparing several forecasting methods, the Prophet model was selected and utilised for forecasting. The model was tested using different outlier detection methods and two settings via a train–test split method (training on 1995–2017 and testing on 2018–2023). To validate the forecast results, the forecast accuracy is measured by Mean Absolute Percentage Error (MAPE). The model settings and outlier-handling combination with the lowest average MAPE across all countries are selected for final projections.

Annual forecasts for 2025–2050 are generated using the chosen configuration. These country-level projections are then disaggregated to the three most populated cities per country, creating spatially realistic demand nodes for the MILP in chapter 6. This validated forecasting approach directly addresses sub-question 2 by supplying robust demand inputs for subsequent optimisation.

2.1.3 Mathematical Modelling

With all relevant input data now prepared, the next step involves formulating the core optimisation model – a MILP that simultaneously determines strategic investment and distribution decisions in the cement supply chain. Specifically, the model maximises profit over a 25-year horizon by choosing which carbon capture technology (or the baseline process) to install at each plant (a binary decision) and how much cement to transport along each route (a continuous decision). The objective function balances revenues from meeting regional demand against production costs, transportation expenses, emission-related charges (including carbon taxes and the CBAM levies), storage and transport costs for captured carbon, and upfront investment costs for new capture technologies. Key constraints include supply capacity (including retrofit downtime), demand satisfaction, annual investment budgets, technology readiness, the non-reversibility of technology choices, and market-share limits per continent. By solving this MILP for two cases – where the CBAM is inactive and where the CBAM is active – it can be quantified how carbon pricing policies and the CBAM reshape both plant-level technology uptake and global cement flows. Full model structure, notation, objective function, and constraints are detailed in chapter 6, providing the foundation for the scenario and sensitivity analyses in chapter 7.

2.1.4 Sensitivity and Scenario Analysis

Following the baseline modelling, two complementary analyses probe the robustness of the findings and explore alternative futures.

Firstly, a sensitivity analysis evaluates the impact of key input parameter uncertainty on optimal investment and distribution outcomes. The following parameters are varied one at a time around their baseline values:

- Production costs;
- Transportation costs;
- Transportation and storage costs[1]; and
- Investment costs.

Resolving the MILP with varying values for the cost parameters identifies which parameters produce the most significant deviations in the output, thereby testing the reliability of the optimisation results under data uncertainty.

A scenario analysis examines the effects of alternative policy pathways by comparing three carbon-pricing trajectories; each run both without and with the CBAM:

- Stated Policies (STEPS) scenario;
- Announced Pledges (APS) scenario; and
- Net Zero Emissions by 2050 (NZE) scenario.

The combination of the carbon pricing scenarios with and without the activation of the CBAM yields a total of six model runs. Comparison across these runs reveals how progressively stringent carbon prices, along with the addition of a border levy, shift the geography of capture investments, redistribute global cement flows, and alter Europe's market share over time.

Both analyses, detailed in chapter 7, serve to validate the stability of results under parameter uncertainty and illustrate how differing policy trajectories shape decarbonisation pathways in the global cement supply chain.

The methodologies employed in this study are fundamental to addressing the research questions, as they collectively support the optimisation of the cement supply chain, the evaluation of carbon-reducing technologies, and the assessment of the CBAM's impact. The research provides a robust framework for evaluating the cement supply chain under different policy conditions. The inclusion of sensitivity and scenario analyses strengthens the credibility of the findings by assessing their robustness across a range of assumptions and potential future developments.

The following chapter presents the first part of the literature review, which forms the theoretical and contextual foundation of this thesis. It begins with an exploration of scientific and industry sources to identify background knowledge – information that is essential for defining the model parameters used in the MILP framework.

[1] The cost of transporting and storing the captured carbon at a cement production plant.

Chapter 3

Theoretical Background

The purpose of this chapter is to establish the theoretical and contextual foundation for the research. It does so by examining the current state of the cement industry, the regulatory environment shaping its operations, and the technologies available for reducing its carbon footprint. This literature-based exploration is essential not only for informing the modelling approach adopted later in the thesis but also for identifying the key drivers of cost and emissions that influence investment and distribution decisions in the cement supply chain.

The methodology employed in this chapter is a structured literature review that encompasses scientific publications, industry reports, official legislative sources, and insights from consultancy and international policy institutions. This approach is used to collect relevant insights on cement production, carbon pricing policies, cement supply chain, and carbon capture technologies. Through this review, the chapter addresses sub-question 1.

In doing so, the chapter lays the groundwork for the development of an integrated optimisation model. The insights derived here guide the selection of variables and parameters that will later be operationalised through data collection and mathematical modelling.

3.1 Regulatory Background and Context

The cement industry has experienced substantial growth over the past century, primarily driven by rapid urbanisation, industrialisation, and infrastructure development. From approximately 200 million tons annually in 1950, global cement production surged dramatically to about 6.2 billion tons by 2015 – a 31-fold increase within just 65 years (Head et al., 2021). Despite a recent stabilisation of around 4 billion tons per year, projections still estimate an annual growth rate of approximately 5.3% up to 2030 (Global Cement, 2023). This continuous growth significantly amplifies the industry's environmental impact, particularly its substantial contributions to global carbon emissions.

The rapid expansion of cement production and its associated carbon emissions have raised urgent sustainability concerns, prompting the implementation of regulatory responses aimed at curbing environmental impacts (Climate Bonds Initiative, 2023). These responses are closely tied to broader climate objectives, such as the EU's legally binding targets to achieve a 55% reduction in greenhouse gas emissions by 2030 and climate neutrality by 2050 (European Commission, 2020, 2023a). Central among these responses have been carbon pricing mechanisms, which emerged as critical policy tools designed to incentivise emission reductions by placing economic costs on carbon emissions.

Among these pricing schemes is the EU ETS. The EU ETS set emission caps on major industries (European Commission, 2023c), including cement production (European Commission, 2024c), by allocating tradable emission allowances to firms. This market-driven approach sought to encourage industries to reduce emissions efficiently through trading and investments in cleaner technologies (European Commission, 2024a). The EU ETS inadvertently leads to competitive disadvantages for regulated European firms. These disadvantages, driven by higher compliance costs, raised concerns about carbon leakage, a phenomenon where firms may shift production to regions with less stringent emission regulations or consumers switching to other products where lesser or no carbon price is levied, potentially undermining global emission reduction goals (European Commission, 2024b; Hayes et al., 2024).

Carbon pricing mechanisms, such as the EU ETS, have significant implications for the cement industry. For instance, the implementation of carbon taxes and emissions trading schemes influences production decisions and supply chain strategies. Tsai and Lin (2024) discusses how such pricing schemes affect overall production planning and corporate decision-making, emphasising the importance for enterprises to adopt a holistic approach. This includes proactively investing in sustainable production methods and advanced technologies to enhance long-term competitiveness and align economic objectives with environmental responsibilities.

The identified limitations and challenges associated with the EU ETS have driven the development of the new complementary regulation, namely the CBAM. This upcoming regulation aims specifically to address carbon leakage and competitive inequities, setting the stage for shifts in global cement industry decarbonisation strategies.

3.1.1 CBAM Regulation

The CBAM is the EU's latest regulatory tool designed to address carbon leakage and ensure that imported goods are subject to equivalent carbon costs as domestically produced ones under the EU ETS. The CBAM officially entered its transitional phase in October 2023 and will become fully operational in 2026 (European Commission, 2024b). Unlike the EU ETS, which allocates emission allowances for domestic producers and facilitates internal carbon trading, the CBAM requires EU importers to purchase certificates reflecting the embedded emissions of imported goods. The certificate price is linked to the average weekly EU ETS allowance price, and importers must annually surrender certificates corresponding to the declared emissions. If a carbon price has already been paid in the country of origin, this amount can be deducted accordingly, ensuring a more fair level playing field between EU producers and foreign competitors.

Conceptually, the CBAM introduces a new approach to climate policy by integrating trade and environmental regulation. Economically, it functions as a border tariff on carbon: importers are required to purchase the CBAM certificates, the price of which mirrors the EU ETS allowance price, corresponding to the carbon content of the imported product. The CBAM accounts for both direct and indirect emissions (European Commission, 2023d). Direct emissions include those generated during the production of the CBAM goods. Indirect emissions refer to the emissions generated from the electricity used during production. Notably, the CBAM does not cover Scope 3 emissions, such as those associated with upstream transportation or the production of raw materials (KPMG LLP, 2024; U.S. Environmental Protection Agency, 2024). The mechanism initially covers sectors at high risk of carbon leakage, including cement, steel, aluminium, fertilisers, electricity, and hydrogen (European Commission, 2024b).

For the cement industry, the CBAM has implications. Strategically, it changes investment calculations, making low-carbon technologies and cleaner production methods more attractive due to the cost burden imposed on high-emission imports. Additionally, it may influence sourcing decisions, logistics, and supply chain configurations (Voigt et al., 2025).

The CBAM differs from earlier mechanisms, such as the EU ETS, in several key respects. Most notably, the CBAM applies specifically to imported goods rather than focusing solely on domestic emissions. While the EU ETS is based on the allocation and trading of emission allowances within the EU, the CBAM introduces a system where importers must purchase certificates reflecting the carbon emissions embedded in imported products (Belastingdienst, n.d.). This ensures that imported goods are subject to equivalent carbon costs as those produced within the EU, thereby addressing competitiveness concerns and discouraging carbon leakage. The mechanism is applied uniformly to all non-EU27 producers covered under the CBAM-regulated sectors, such as cement, reinforcing climate ambitions through trade policy.

Starting in 2026, the CBAM will begin replacing the free allocation of emission allowances under the EU ETS for sectors covered by the mechanism, including the cement sector. A transitional phase-out has been defined, during which the share of free allowances is gradually reduced through a declining CBAM factor (European Union, 2023). This provides producers with the necessary time to adapt to the new regulatory regime. The exact values of the CBAM factor are used as inputs to the optimisation model and are provided in Appendix A.

The United Kingdom (UK) will introduce its own CBAM in 2027, covering sectors such as cement, aluminium, iron and steel, and hydrogen. The UK CBAM is expected to closely mirror the EU's design, with the key difference being that importers will begin paying from 2027, one year later than in the EU (Department for Energy Security & Net Zero, 2025). While the UK government recognises the need to adjust free ETS allowances in line with the CBAM, it has not yet published a detailed year-by-year phase-out schedule. UK Government (2024) states that the free allocations are largely carried over from the EU ETS free allocation. Therefore, this study will model the UK ETS and CBAM similarly to the EU ETS and CBAM, with the only difference being the later start date of the UK's CBAM.

As a result, the CBAM represents a critical evolution in carbon pricing policy, not only reinforcing the EU's climate goals but also reshaping the strategic landscape for cement producers both inside and outside Europe.

Understanding how the CBAM and other carbon pricing mechanisms affect strategic decisions is only one part of the equation. To fully understand the implications of these policies, it is essential to examine how they impact the structure and operation of the cement supply chain. The following section (section 3.2) therefore examines the main stages of the cement supply chain, identifying key cost and emissions drivers that determine where and how decarbonisation measures can be most effectively applied.

3.2 Cement Supply Chain

Various stages characterise the cement supply chain, each contributing distinctly to the overall cost and environmental footprint of cement production. Identifying these costs and emissions drivers throughout the supply chain is critical, as it answers sub-question 1 by pinpointing where significant interventions and optimisations can occur.

The cement supply chain can be broadly divided into three main stages:

1. The inbound of raw materials;
2. The production process; and
3. The distribution to clients.

Figure 3.1 illustrates these stages along with the approximate share of carbon emissions attributed to each stage (Czigler et al., 2020).

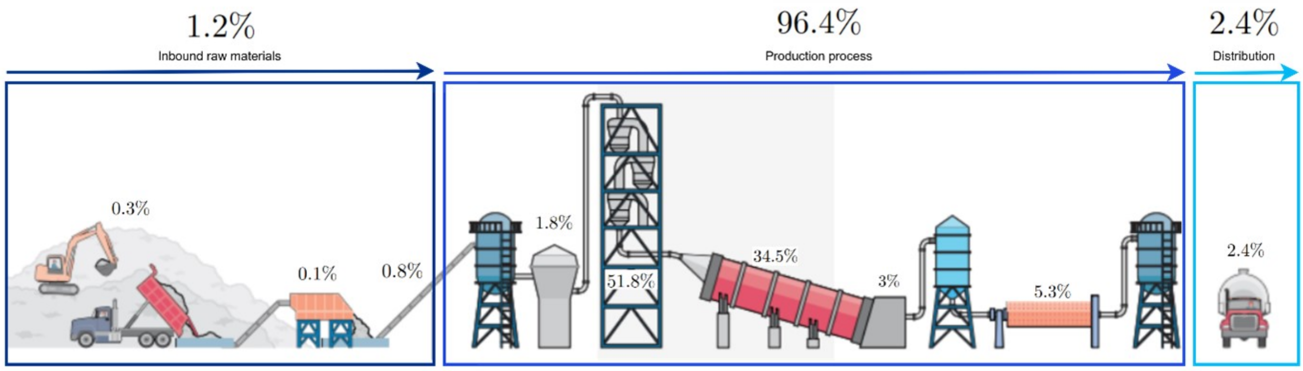

Figure 3.1: Cement supply chain with the emissions shown in percentages. Adapted from Czigler et al. (2020).

3.2.1 Inbound of Raw Materials

The initial stage of the cement supply chain involves acquiring and preparing raw materials, mainly limestone and clay. These materials are mined, crushed, and transported to cement plants for further processing and use. This stage accounts for a minor proportion of emissions – approximately 1.2% of total supply chain emissions – primarily originating from machinery operations and the use of transportation fuels. This phase is highlighted in the leftmost section of Figure 3.1.

This part of the supply chain is excluded from the model due to its limited expected sensitivity to carbon pricing mechanisms and the defined scope of the study.

3.2.2 Production Process

The cement manufacturing stage is central to both cost structure and environmental impacts within the supply chain. This phase is notably energy-intensive and emission-heavy due to its reliance on high-temperature processing and chemical reactions. This step contributes the most to overall emissions, approximately 96.4%.

Once the raw materials are stored, the production process begins. The primary sources of these emissions are the chemical decomposition of limestone ($CaCO_3$) into calcium oxide (CaO) and carbon dioxide (CO_2), as well as the combustion of fuel. High temperatures are required in the preheater and rotary kiln, leading to fuel combustion and associated carbon emissions (Cormos, 2022). These two steps together account for a significant portion (around 86.3%) of the total emissions in the production stage.

Figure 3.2 illustrates the breakdown of carbon emissions during the production of cement (Lowitt, 2020). This chart highlights the contributions of various stages, including calcination, thermal energy use, transportation, and electricity. Notably, it also identifies the portion of emissions that is unavoidable for Ordinary Portland Cement (OPC). The "unavoidable" emissions reflect the carbon dioxide released solely through the chemical transformation of limestone.

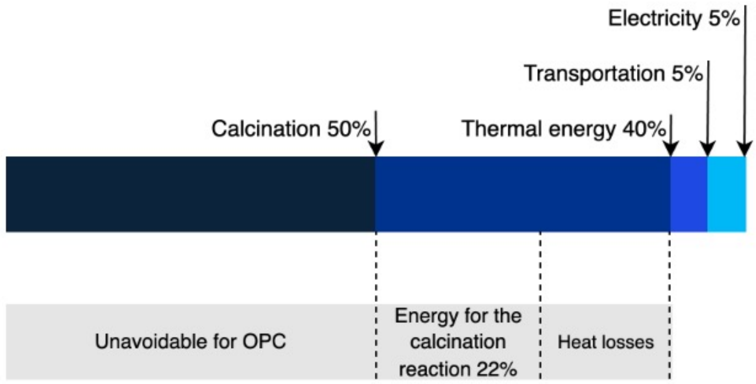

Figure 3.2: The percentages of carbon emission during the production of cement (Lowitt, 2020).

Given the high share of emissions generated during calcination and fuel combustion, various strategies have been proposed to mitigate the environmental impact of cement production. Such strategies include carbon capture, alternative raw materials, and alternative fuels (Ige et al., 2024). Employing these strategies can help reduce the overall carbon footprint.

The manufacturing process is thus identified as the critical stage for strategic emission reduction interventions, given its high emission intensity. Therefore, this stage serves as the focus for strategic investment decisions.

Considering the significant emissions generated during cement production, particularly from calcination and fuel combustion, carbon capture technologies emerge as a highly effective investment strategy to reduce emissions substantially. Among these, post-combustion, oxy-fuel combustion, and direct separation technologies are selected for this research due to their significant emission reduction potential (Cormos, 2022; Driver et al., 2022; Gerbelová et al., 2017). While a range of alternative decarbonisation measures exists – such as fuel switching and the use of alternative raw materials – this study focuses solely on carbon capture technologies due to their high potential for emission reduction and the relatively limited academic attention given to their strategic integration in investment decision-making (Ige et al., 2024). A broader analysis of mitigation options was beyond the scope of this study.

3.2.3 Distribution of Cement

Following manufacturing, cement is distributed to various customers and regions. While transportation emissions are not affected by the CBAM, distribution remains economically significant due to the transportation costs associated with moving bulk cement.

Moreover, the introduction of carbon taxes in regulated regions may influence distribution strategies. Cement produced with lower direct carbon emissions will ideally be prioritised for distribution to regions where carbon emissions carry a regulatory price, including EU countries regulated by mechanisms such as the CBAM. This strategy could significantly alter the optimal distribution logistics, as producers aim to minimise regulatory associated costs by aligning their distribution decisions accordingly.

In summary, the cement supply chain consists of three primary stages: inbound logistics, production, and distribution, with the production process accounting for the vast majority of emissions. At this stage, calcination and fuel combustion account for over 96% of total supply chain emissions, making them the most critical points for intervention. While upstream and downstream processes play important economic and logistical roles, meaningful decarbonisation hinges on mitigating emissions generated during production. This underscores the strategic relevance of investment decisions targeting emission-intensive technologies. Among the available mitigation pathways, carbon capture technologies stand out for their ability to directly reduce emissions at the source. The following section, therefore, reviews the state of carbon capture in the cement sector, providing the technological foundation for the investment decisions explored in this study.

3.3 Carbon Capture Technologies

The cement industry is a significant contributor to global carbon emissions, accounting for approximately 6–8% of anthropogenic carbon emissions. Emissions originate not only from fossil fuel combustion but also from the calcination of limestone, which is an inherent part of clinker production. While improvements in energy efficiency and fuel substitution can offer emission reductions, they are insufficient to meet long-term decarbonisation targets (Cormos, 2022; Li et al., 2013). For this reason, Carbon Capture and Storage (CCS) is considered an essential component of a low-carbon cement industry, particularly for reducing process emissions that cannot be avoided otherwise (Gerbelová et al., 2017; Hendriks et al., 1998). This section introduces three carbon capture technologies – post-combustion capture, oxy-fuel combustion, and direct separation – that are considered in the modelling approach of this thesis. The rationale for their inclusion is based on technical feasibility and industrial relevance.

3.3.1 Post-Combustion

Post-combustion capture is the most mature carbon capture technology and is already used commercially in other sectors such as natural gas processing and power generation (Bosoaga et al., 2009). In cement production, it involves removing carbon from flue gases after combustion, typically using chemical absorption with amine-based solvents.

One of the primary advantages of post-combustion systems is their potential for retrofitting. Since they treat flue gas after the combustion and clinker production processes, they can be added to existing plants with minimal interference to core operations. According to Li et al. (2013) and Hills et al. (2016), this makes post-combustion capture particularly attractive for upgrading current cement facilities. For this reason, they are among the most likely candidates for early commercial deployment in cement carbon capture.

3.3.2 Oxy-fuel Combustion

Oxy-fuel combustion involves burning fuel in pure oxygen rather than air, resulting in a flue gas primarily composed of carbon and water vapour, which can be easily separated by condensation (Cormos, 2022). In the context of cement production, substantial modifications to the kiln system are required, including the integration of an air separation unit and adaptation of the combustion process (Gerbelová et al., 2017).

It is important to distinguish between full and partial oxy-fuel configurations. While complete oxy-fuel combustion systems are capable of achieving high carbon capture rates, they are generally considered unsuitable for retrofitting due to the need for extensive redesigns of nearly all process units, resulting in high capital costs and long shutdown periods. As noted by Hills et al. (2016), complete oxy-fuel systems are more likely to be viable only in new-build low-carbon cement plants. In contrast, partial oxy-fuel systems are considered more retrofit-friendly. They offer a compromise between feasibility and capture performance, with retrofit implementations requiring less intrusive modifications and shorter shutdown durations.

3.3.3 Direct Separation

Direct separation represents an approach specifically tailored to the calcination process (Driver et al., 2022). Instead of mixing combustion gases with process emissions, direct separation systems isolate the calcination reaction in a separate reactor, typically heated indirectly, which enables the capture of a nearly pure stream of carbon.

Driver et al. (2022) reports that this technology can capture nearly all of the process-related carbon emissions from calcination with minimal thermal penalty and modest increases in electricity use.

According to Hills et al. (2016), direct separation technology is relatively retrofit-friendly. Although it requires replacing the preheaters and precalciner, the kiln and cooler sections remain essentially unchanged, simplifying integration. Its modular reactor design may also enable prefabrication, which helps reduce on-site construction time and shutdown periods. These characteristics position direct separation as an attractive option for both retrofits and new builds.

Despite its retrofit potential and promising emission reduction capabilities, direct separation is not included in the optimisation model developed in this thesis. This exclusion is primarily due to the absence of reliable, publicly available techno-economic data – specifically, investment costs and production costs necessary for model implementation. As noted by Hills et al. (2016), although the technology demonstrates strong technical feasibility, uncertainties persist regarding cement quality outcomes, and no detailed cost assessments have been published to date. Without these inputs, a fair and accurate comparison with other capture technologies would not be possible.

The model developed in this thesis incorporates two carbon capture technologies: post-combustion capture and partial oxy-fuel combustion. These technologies are among the most relevant for the cement sector due to their retrofit potential, emission capture rates, technological maturity, and the availability of supporting techno-economic data required for implementation in optimisation models.

The implementation of carbon capture technologies in the cement industry involves not only technical feasibility but also complex decision-making regarding when and where to invest, as well as how such investments interact with distribution choices. These are strategic decisions that can benefit from formal optimisation models capable of addressing economic trade-offs and constraints. To explore whether existing decision-support tools can accommodate such challenges or whether new approaches are required, the following section reviews state-of-the-art modelling efforts aimed at reducing the environmental impact of cement production.

3.4 Current Optimisation Models

Table C.1 presents a comparison of five modelling methods applied to cement industry decarbonisation: System-Dynamics (SD) simulation, Life-Cycle Assessment (LCA), Agent-Based (AB) modelling, Multi-Criteria Decision Making (MCDM), and MILP. Each entry summarises the problem scope, core methodological strengths and limitations, and reference.

Table 3.1: Comparison of modelling paradigms for cement industry decarbonisation.

Model type	Problem scope	Strengths	Limitations	Reference
SD simulation	Review and comparison of system-dynamics models assessing various carbon-mitigation strategies in the cement industry	• Captures non-linear feedbacks and time delays across the full cement value chain • Flexible "what-if" policy experimentation across multiple mitigation levers	• Not an optimisation model (no explicit decision variables or optimal investment allocation) • Aggregates at industry scale	(Ige et al., 2024)
SD simulation	Comparative review of how system-dynamics models have been applied to evaluate carbon-mitigation strategies in the cement industry	• Captures non-linear feedbacks, time delays, and dynamic interactions across the cement value chain • Enables flexible "what-if" policy and scenario experimentation over multi-decadal horizons	• Lacks explicit decision variables and optimisation logic • Aggregates at a high (industry or sector) level, so it cannot resolve plant-level or discrete investment choices	(Kunche & Mielczarek, 2021)

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Table 3.1 – continued from previous page

Model type	Problem scope	Strengths	Limitations	Reference
LCA	Providing a standardised guideline for conducting LCA of CCU technologies	• Defines a harmonised framework that enhances transparency and comparability across CCU LCAs	• LCA is usually static and does not optimise investment decisions or capture cost-minimisation trade-offs • Aggregates at a high (industry or sector) level, so it cannot resolve plant-level or discrete investment choices	(Müller et al., 2020)
AB modelling	Simulating the investment decisions of heterogeneous industrial investors in the Chinese ammonia sector – assessing fuel switching and CCS uptake	• Represents diverse investor goals • Non-linear system effects	• No optimum guarantees • It's tricky to ensure coherent, system-wide investment consistency.	(Sachs et al., 2019)
MILP	Designing and optimising a multi-period CCS/CCU supply-chain network for the Austrian cement industry, under uncertain data entries	• Finds globally optimal investment and operational strategies under explicit scenario-based uncertainty • Integrates prospective LCA impacts directly into the optimisation	• Inability to handle nonlinearity • Can be computationally expensive	(P. Wang & Papadokonstantakis, 2024)

Continued on next page

Table 3.1 – continued from previous page

Model type	Problem scope	Strengths	Limitations	Reference
MILP	Selecting optimal sites for new cement plants and assigning raw-material flows from mines to plants and finished-product flows from plants to demand centres, balancing environmental and economic goals under uncertainty	• Explicitly models multiple, possibly conflicting objectives via fuzzy goal-programming • Incorporates stochastic chance-constraints to handle demand and capacity uncertainty	• Inability to handle nonlinearity • Can be computationally expensive	(Bakhtavar et al., 2019)
MCDM	Prioritising energy-efficiency measures for individual cement plants by integrating plant-specific technical, economic, and qualitative criteria	• Combines quantitative and qualitative criteria in a single framework	• Does not solve an optimisation problem or allocate investments optimally – only ranks alternatives without cost-minimisation guarantees • Relies on stakeholder judgment for weights (AHP) and scalar scoring (TOPSIS), introducing subjectivity and lacking uncertainty treatment	(Mokhtar & Nasooti, 2020)

Table C.1 categorises five distinct approaches to cement industry decarbonisation. SD and LCA models excel at depicting value chain feedbacks and benchmarking environmental impacts, but do not formulate optimisation problems or generate discrete investment plans. AB and MCDM tools introduce behavioural heterogeneity and structured ranking of alternatives, yet lack guarantees of global optimality and cannot simultaneously resolve binary retrofit decisions and continuous transport flows. In contrast, the MILP formulations provide a solver-based framework that can model investment and distribution variables under a unified objective.

The above-mentioned techniques, excluding the MILP, are ill-suited to address the tightly coupled decision environment induced by the CBAM, where the decision on where to invest and how to distribute the cement is made. The core research question requires simultaneous treatment of binary choices and continuous trade flows. MILP captures this integration by defining binary variables for retrofit decisions and modelling continuous distribution flows. This technology can identify the globally optimal strategies that balance revenues and all the cost components over the planning horizon.

Although the MILP framework imposes linear relationships – thereby excluding explicit representation of non-linear phenomena such as economies of scale – the principal cost and emission parameters can be approximated via linear functions. Carbon costs remain constant per ton of carbon emitted. In contrast, transport costs are volume-dependent; because distribution is aggregated on an annual basis, this linearisation does not influence the model's dynamics. Similarly, production costs are treated as linear under the assumption that cement plants operate sufficiently close to design capacity, rendering unit production costs effectively constant over the planning horizon.

A closer examination of existing MILP studies further illuminates the gap addressed in this study. P. Wang and Papadokonstantakis (2024) formulate a multi-period stochastic MILP for co-optimising carbon capture, transport, storage, and utilisation across nine Austrian plants under scenario-based uncertainty; however, their focus on a single country and omission of the CBAM limits applicability to global supply chains. Bakhtavar et al. (2019) extends MILP with fuzzy multi-objective and stochastic chance constraints to optimise new plant locations and material flows, yet does not incorporate carbon pricing mechanisms or distribution costs tied to emissions. Meanwhile, Mokhtar and Nasooti (2020) offers a hybrid decision support tool for ranking energy efficiency measures at individual plants but does not solve a unified optimisation problem for investment and transport under policy uncertainty. Collectively, these studies demonstrate MILP's capability for discrete investment and continuous flow optimisation under uncertainty, while also revealing a lack of integration of the carbon pricing mechanism, the effect of the CBAM, and investment and distribution decisions in a single model.

For those interested in further exploring optimisation models in the cement industry, additional references include studies by Dinga and Wen (2022), Ishak and Hashim (2022), Karbassi et al. (2010), and Ogbeide (2010), which discuss various aspects of environmental impact optimisation within the industry.

In summary, while these models contribute valuable insights into emission reduction and cost optimisation, they fail to address a critical element: the integrated relationship between investment and distribution decisions under an evolving carbon pricing landscape. This limitation motivates the next step in this research, which is to extend the modelling framework. This will be done by addressing it as a Transportation Problem (TP).

3.5 Transportation Problem

In traditional operations research, the TP is used to determine the most cost-effective way to distribute goods from multiple origins to multiple destinations, minimising total transport costs while satisfying supply and demand constraints. Globally, carbon pricing mechanisms are introducing new economic considerations into distribution decisions. One such regulation is the CBAM, which imposes carbon costs on imported goods based on their embedded emissions. As a result, the cost of supplying cement to a given market is no longer driven solely by transportation and production costs but also by the emissions generated during cement production.

This research uses the classical TP framework to incorporate these regulatory costs, linking each supply route to economic distance and the carbon cost of production under different jurisdictions. This model provides a foundation for evaluating how climate policies such as the CBAM shape cross-border cement flows and investment decisions.

The TP is a mathematical problem formulated by Hitchcock (1941). He states the problem as a cost minimisation problem of distributing products produced in several factories to numerous cities. The cost of moving the product between factories and cities depends on factors such as freight rates and varies for every combination of factories and cities. To solve the problem, an $m \times n$ matrix of decision variables x_{ij} (where $i \in 1, 2, \ldots, m$ and $j \in 1, 2, \ldots, n$) must be determined, representing the number of product units distributed from origin i to destination j, to minimise total cost (Ford Jr & Fulkerson, 1956). While optimising this, the available supply at the factories and the demand in the cities have to be satisfied.

There are many applications of the TP in the literature, each with its adjustments. For example, Ford Jr and Fulkerson (1956) applies the TP to minimise the shipping costs of moving commodities from warehouses to plants that are having shortages of this commodity. The TP, in this case, is balanced, meaning that the sum of the supplies equals the sum of the demands. Dantzig (2016) discusses a non-balanced TP. Here, the number of cases produced in two canneries has to be sent to three warehouses. The total sum of the demands of the warehouses is lower than the total supply available at the canneries. The excess production will not be sent to a warehouse. Both models minimise the total shipping costs associated with product distribution. The problem addressed in this thesis will not be balanced.

In the problem addressed in this thesis, the supply nodes represent the production plants, and the clients of the cement company represent the demand nodes. In the transportation models discussed earlier, the costs of moving a product consist only of transportation-related costs. Notably, this model will introduce several additional cost factors to the transportation of cement from the plants to customers. Among these costs are the expenses associated with the carbon emissions imposed by regulations. Additionally, this study will include a binary decision variable indicating whether an investment has been made at a specific node. Figure 3.3 presents a simple graphical representation of the problem, utilising a bipartite graph with three supply nodes and four demand nodes. In the context of this thesis, production plants serve as supply nodes, and the cement company's customers represent demand nodes. The arcs illustrate the potential distribution lines and carry the costs of distributing x_{ij} amount of units of cement from production plant i to customer j. As shown in the figure, the costs considered on the arcs comprise production cost, emission cost, transportation cost, and transport and storage costs of carbon.

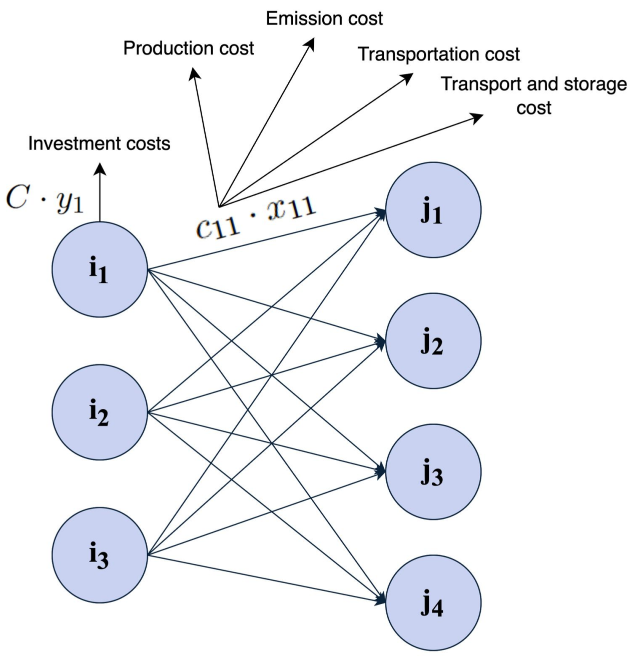


Figure 3.3: Graphical representation of the Transportation Problem framework employed in this study.

By capturing these multi-dimensional costs, the model establishes a robust structure for evaluating supply chain strategies under evolving policy conditions. To make this framework operational, the next chapter (chapter 4) outlines the data required to parameterise the model.

This chapter lays the theoretical and contextual foundation for the research by examining the key elements that shape the cement industry's decarbonisation landscape. The review began by examining the regulatory evolution of the cement sector, with a particular focus on carbon pricing mechanisms, such as the EU ETS and the recently introduced CBAM. The strategic implications of these policies were highlighted, demonstrating how they alter both investment incentives and distribution decisions.

The chapter then explored the structure of the cement supply chain and identified the main emission drivers across inbound logistics, production, and distribution. Special attention was given to the production stage, which accounts for the majority of emissions, thereby justifying its central role in decarbonisation efforts. In this context, three carbon capture technologies were introduced and assessed: post-combustion, (partial) oxy-fuel combustion, and direct separation. Although all three are technologically promising, only the first two are included in the optimisation model due to the lack of reliable techno-economic data for direct separation.

Following this, an assessment of the existing body of optimisation models demonstrated that most prior approaches either neglect the integration of the CBAM or fail to consider strategic investment and distribution decisions simultaneously. These limitations motivated the development of the TP modelling framework, which can incorporate multi-dimensional cost structures, including carbon pricing and the option to invest in one of the carbon capture technologies.

Having established this conceptual foundation, the next chapter turns to the practical task of collecting the data required to operationalise the model. In chapter 4, the data sources and assumptions used to construct the model's input parameters are outlined, directly building on the insights and requirements identified in this literature review.

Chapter 4

Data

To evaluate the cement supply chain under cost and emissions considerations, the TP introduced in the previous chapter requires robust and context-specific data inputs. These data underpin the model's ability to reflect real-world dynamics – ranging from production and transport costs to emission intensities and policy-driven carbon prices. Without such data, the model would remain theoretical and disconnected from practical decision-making contexts.

This chapter addresses the second sub-question by detailing the whole process of preparing the model's input data. First, it outlines the types and sources of data required, including those related to production, demand, transport, emissions, and policy instruments. Next, it introduces the scenario framework that will be applied later to analyse the effects of policy uncertainty on model outcomes.

4.1 Data Collection

To provide the optimisation model explained in section 3.5 with the necessary input, various types of data must be collected. Data is needed to model the cement plant nodes, the costs, and the demand nodes. These data entries will be discussed in detail in the following sections.

4.1.1 Global Cement Assets Dataset

Data on cement manufacturing plants is essential to model the supply nodes of the TP. Specifically, the model requires information on the locations, capacities, and ownership of the plants. These attributes determine not only where cement can be distributed from but also how much can be supplied and which facilities fall within the scope of the modelled supply chain.

The geographic coordinates of each plant are used to calculate distances to demand nodes, which in turn drive transportation cost calculations. Production capacity serves as a hard constraint, ensuring that no plant supplies more cement than it can realistically produce. Ownership information is necessary to limit the model to facilities operated by a specific company.

This study utilises the *SFI Global Cement Database* – a comprehensive global dataset compiled by Tkachenko et al. (2023) – as the primary source of plant-level information. From this dataset, the following key elements have been extracted:

- **Geographical data:** Includes information such as city, state, country, and geographical coordinates (latitude, longitude), which are essential for spatial mapping of production sites.

- **Plant characteristics:** Provides details on production capacity (measured in millions of tons), thereby facilitating the analysis of production capabilities.

- **Ownership data:** Contains information on parent companies and ownership stakes, offering insights into the industry structure and the distribution of market power.

4.1.2 BACI Bilateral Trade Flows Dataset

In the model, cement is distributed from production plants to the customers of the cement manufacturer. To optimise distribution, forecasts of national cement demand are required due to the scarcity of data on future demand. This, in turn, necessitates the reconstruction of historical demand data. However, consistent and comprehensive data on national cement consumption are not widely available. To address this limitation, an estimation approach is used based on three components: domestic production capacity, cement imports, and cement exports. The domestic capacity data is drawn from the *SFI Global Cement Database* previously introduced in subsection 4.1.1.

For trade data, this study utilises the *BACI Bilateral Trade Flows Dataset* developed by Gaulier and Zignago (2025), which contains detailed bilateral trade flows for approximately 200 countries across 5000 product categories, classified by 6-digit Harmonised System codes. Specifically, import and export quantities are extracted for three types of cement products over multiple years and countries. The selected product categories are:

- **252321:** Portland cement, white, whether or not artificially coloured.
- **252329:** Portland cement, other than white, whether or not artificially coloured.
- **252390:** Hydraulic cement, not elsewhere classified in heading no. 2523.

These categories were chosen because they comprehensively represent the key cement products traded internationally and align with the scope of cement considered in the supply chain model of this study. Their combined coverage ensures that both common Portland cement and more specialised cement are captured in the trade-based estimation of demand.

The resulting import and export data, along with domestic production capacity, form the basis for estimating historical national cement consumption, as described in section 5.1. These demand estimates are then used to forecast future consumption trends, as described in section 5.2. The future consumption trends will be the input of the model representing the demand nodes.

4.1.3 Emission Data

The embedded carbon emissions of cement products are a key parameter for modelling emissions and carbon prices. In this study, direct and indirect emission intensities are based on the default values published by the European Commission for the transitional CBAM period from 1 October 2023 to 31 December 2025 (European Commission, 2023b). These values, derived by the Joint Research Centre and reflecting weighted global averages based on production volumes, serve as benchmarks.

Since this study does not model the three cement types separately, an average emission intensity is calculated based on their global trade distribution, as observed in the *BACI Bilateral Trade Flows Dataset*. Across all available years, the trade shares are 5.79% for white Portland cement (2523 21 00), 87.98% for other Portland cement (2523 29 00), and 6.23% for other hydraulic cement (2523 90 00). Weighted by these shares, the average embedded direct emission is estimated at 0.8165 t CO_{2e} per ton of cement, and for the indirect emissions, 0.061 t CO_{2e}. This value is used uniformly across all modelled cement production plants, based on the assumption that this distribution is representative globally.

Only direct and indirect scope 2 emissions are included in this model, as they are the emissions currently regulated under the CBAM. Indirect scope 3 emissions are currently outside the scope of these regulatory frameworks and are therefore excluded from this study.

Table 4.1: Direct and indirect emission default values transitional period for cement (European Commission, 2023b).

Aggregated goods category	CN code	Description	Direct emissions (t CO_{2e}/t)	Indirect emissions (t CO_{2e}/t)
Cement	2523 21 00	White Portland cement, whether or not artificially coloured	1,16	0.10
Cement	2523 29 00	Other Portland cement	0,81	0.06
Cement	2523 90 00	Other hydraulic cements	0,59	0.04

4.1.4 Transportation Cost

Transportation costs are a critical component of the total cost structure in the TP model. They determine the economic feasibility of distributing cement from production sites to demand regions and play a key role in optimising supply chain flows.

This study utilises transportation cost data from the *UNCTAD Trade and Transport Dataset*, developed jointly by UNCTAD and the World Bank (United Nations Conference on Trade and Development, 2024). The dataset records bilateral trade flows – including transport expenditure and freight metrics – for a wide range of goods, including cement, across economies.

The selected indicator, *per-unit freight rate*, represents the average transport expenditure per kilogram of cement shipped between subregions and is used to populate the transportation cost matrix in the TP model. These values reflect the aggregated cost of transport services, including shipment and insurance, from the exporter to the importer. A detailed explanation of how the data is processed and the transport parameter (τ_{ij}) is constructed can be found in Appendix F.

By integrating freight data with distance-based adjustments, the model captures a nuanced and adaptable view of transportation costs across the global cement supply chain. Transportation cost dynamics can differ significantly even between origin-destination pairs with the same physical distance, or for the same pair when shipment direction reverses. Accurately representing these complexities is essential for building a realistic depiction of the cement supply chain and for generating reliable optimisation outcomes. This approach allows for a more precise evaluation of economic trade-offs along regional supply routes.

4.1.5 Technologies Data

A key objective of this research is to optimise strategic investment decisions aimed at reducing carbon emissions within the cement industry's supply chain. Specifically, the study evaluates the adoption of carbon capture technologies, which are designed to mitigate the financial burden of carbon pricing mechanisms by significantly lowering carbon emissions.

To accurately assess the economic and operational implications of these technologies, data were collected on four core parameters: investment costs, production costs, carbon capture rate, and the expected duration of the retrofit for existing cement facilities. In the optimisation model, carbon capture technologies are introduced as investment options with region-specific parameter values (production costs) to reflect geographic variation in cost structures.

The carbon capture rates for post-combustion and oxy-fuel combustion technologies are estimated at 90% and 65%, respectively, according to Hills et al. (2016). These capture rates, in combination with the direct emissions from the base case scenario, are used to compute the adjusted direct emissions for each technology. The resulting emission factors are then used to determine the carbon costs incurred under different regulatory conditions.

While annual shutdowns typically last around one month and are suitable for routine maintenance or more minor improvements, Hills et al. (2016) note that this type of post-combustion retrofit is likely to be completed within the period of an annual shutdown. As such, the study assumes that the installation of post-combustion technology would be planned to coincide with this existing one-month downtime, resulting in no disruption[1]. In contrast, partial oxy-fuel retrofitting requires more substantial interventions, including the replacement of the precalciner and preheater. Although described as "relatively easy" compared to complete oxy-fuel retrofits, which involve extended shutdowns and raise questions about practicality, the paper indicates that partial oxy-fuel still necessitates a "lengthy shutdown". Given that full plant modernisations may take more than a year, it is assumed that the partial oxy-fuel retrofit will take around one year, reflecting its intermediate installation complexity.

Investment cost estimates for both post-combustion and oxy-fuel combustion technologies are also based on data from Hills et al. (2016). These figures were adjusted for inflation and currency conversion as detailed in Appendix B. The cost intervals provided in the source were used to define a distribution range, meaning that investment costs in the model scale with facility capacity: the smallest facility receives the lower bound estimate, the largest the upper bound, and the remaining facilities are assigned proportionally distributed values in between. This study does not account for potential cost reductions of carbon capture technologies over time.

To validate the accuracy of the estimated investment costs of the post-combustion technology, it is compared with the only full-scale executed carbon capture and storage project in the cement industry, implemented by Heidelberg Materials (Brevik CCS Project, 2025). While the investment cost of the Brevik CCS project ($359 million, as reported by Røsjorde and Carpenter (n.d.)) did not specify the price year, and inflation adjustment was therefore omitted, it was compared directly to the model's estimated cost for a similarly sized plant ($380 million). The resulting deviation, approximately 6%, provides a reasonable degree of confidence in the accuracy of the cost estimates used in this study.

Further detail on the assumptions, data sources, and processing methods used to derive these cost parameters is provided in Appendix G.

4.1.6 Transport and Storage Costs

In the model's objective function, each facility's transport and storage cost parameter is set equal to the lowest per-ton carbon delivery cost across all qualifying sites. Eligible storage locations are drawn from the dataset of IEA (2025), and the total cost is decomposed into:

- Site to transit transport (pipeline, harbour or direct delivery);
- Injection fees at the storage site; and
- Additional shipping costs apply when no nearby storage is available.

Mode-specific base costs are sourced from Roussanaly et al. (2021) (onshore pipelines and harbour shipping), Myers et al. (2024) (truck tankers) and Smith et al. (2021) (storage), then adjusted for annual flow rate, distance (via regression extensions), regional labour-cost differentials and inflation. Full data tables, regression functions and adjustment procedures are provided in Appendix D.

The data collection phase brought together a comprehensive set of inputs required to parameterise the optimisation model. Cement plant characteristics were drawn from the *SFI Global Cement Database*, while national demand nodes were reconstructed from domestic production capacities and *BACI bilateral trade flows*. Embedded emission factors were set using the CBAM default intensities provided by the EU, and freight rates were populated from the *UNCTAD Trade-and-Transport Dataset* with distance-based

[1] The production capacities of the plants are assumed to already account for the effects of the annual shutdown period.

adjustments. Investment, production and retrofit costs for post-combustion and oxy-fuel combustion technologies were indexed to plant size. Finally, carbon transport and storage tariffs were compiled and then scaled for flow rate, distance, regional labour cost differentials and inflation.

With the full parameter suite established, the following section introduces the scenario design, detailing the carbon-price trajectories that will shape the model's simulation runs.

4.2 Scenario Design

To ensure the robustness and policy relevance of the optimisation results, this study incorporates a set of scenarios that reflect potential future developments in carbon pricing. These scenarios aim to test the model's sensitivity to plausible variations in market and regulatory conditions. This section defines the scenario inputs that will later be applied in the scenario analysis phase.

Future developments in climate policy, particularly the adoption and strengthening of carbon pricing mechanisms, represent a significant source of uncertainty for investment decisions in the cement industry. To reflect these dynamics, this study incorporates three carbon price trajectories.

Three carbon price pathways are derived from (IEA, 2024), which differ in their underlying policy ambition (in the eyes of the IEA):

1. The STEPS, which includes only those policies already in law or at an advanced stage of being adopted;

2. The APS, which adds all announced policies regardless of the IEA's assessment of their practical feasibility; and

3. The NZE, a normative, backwards-looking pathway that specifies the actions required to achieve net-zero emissions by mid-century.

This set of scenarios enables the model to account for both conservative and highly ambitious decarbonisation pathways, enhancing policy realism in the analysis.

Carbon prices are applied to emissions from cement production and differ by International Energy Agency (IEA) scenario and region. In the STEPS variant, prices are specified on a country-by-country basis rather than by cluster. This study assumes the EU line to include the EU27 Member States according to Centraal Bureau voor de Statistiek (2025) plus all jurisdictions covered by the EU ETS – Norway, Iceland, Liechtenstein and Switzerland – and the UK.

In the APS and NZE variants, countries are grouped into three clusters:

- Advanced economies with NZ pledges;
- Emerging markets with NZ pledges; and
- Other emerging markets.

Assignment to "advanced" or "emerging" follows the IMF's World Economic Outlook classifications (International Monetary Fund, 2023); emerging markets are then split into those with and without net-zero pledges based on IEA pledge data (International Energy Agency, 2025).

Prices are taken from IEA tables at intervals (2030, 2035, 2040, 2050). For STEPS, all EU ETS jurisdictions follow the EU trajectory, with the UK assumed to follow a similar path. To capture the phase-out of free allowances under the EU ETS, the effective carbon cost per ton of cement is adjusted by the CBAM phase-out factors described in subsection 3.1.1 (see also Appendix A).

Table 4.2 reports the resulting carbon prices for each scenario and region used in the model.

Table 4.2: Carbon prices in USD indexed to 2025 per ton under IEA scenarios by region and year (IEA, 2024).

Scenario	2030	2035	2040	2050
STEPS (Stated Policies)				
European Union	147	152	156	165
China	41	45	48	54
Chile and Colombia	22	25	29	29
Korea	59	68	76	93
Canada	132	132	132	132
APS (Announced Pledges)				
Advanced economies with NZ pledges	141	167	183	209
Emerging markets with NZ pledges	42	68	115	167
Other emerging markets	–	6	18	49
NZE (Net Zero Emissions by 2050)				
Advanced economies with NZ pledges	147	188	215	262
Emerging markets with NZ pledges	94	131	167	209
Other emerging markets	16	26	36	57

This structured approach ensures that the cost of emissions in the model reflects a realistic and regionally differentiated view of carbon pricing evolution, providing a robust foundation for analysing the financial implications of decarbonisation policies under multiple regulatory futures.

This chapter has assembled and harmonised the core data inputs required for the optimisation model, including plant-level characteristics, emission factors, transport rates, carbon capture technology costs, and carbon transport and storage tariffs. Additionally, it defines three regionally differentiated carbon price trajectories (STEPS, APS, and NZE) to capture a range of policy ambitions. However, one final step remains: forecasting future cement demand to establish the demand nodes in the model. Once completed, this will provide the full set of inputs necessary to implement the optimisation model in chapter 6.

With plant capacities, imports and exports assembled, the next chapter (chapter 5) will generate the missing country-level demand forecasts – completing the input dataset needed before developing the model.

Chapter 5

Forecast

This chapter presents the methodology and results of the cement demand forecasting process, which serves as a critical input to the optimisation model developed in this thesis. Accurate forecasts of future demand are essential for informing investment and distribution decisions in the cement supply chain.

The objective is to generate reliable, country-level demand projections over the period 2025–2050. These projections are used to define the demand nodes within the model and to evaluate how various technologies and policies impact optimal supply chain configurations. The chapter begins with a discussion of the data preparation steps and forecasting methodology, followed by an explanation of outlier treatment procedures and model configuration. It concludes with a validation of the forecast performance to ensure its credibility and suitability for use in the subsequent optimisation model.

5.1 Data Processing

Before forecasting future cement demand, the datasets identified through the literature review were processed to create a unified, country-level dataset spanning the period from 1995 to 2023. Two primary data sources were used:

1. The *Global Cement Assets Dataset*, which contains detailed information on cement production facilities, including production capacities and geographical coordinates.
2. The *BACI Bilateral Trade Flows Dataset*, which provides data on trade flows of cement products, including import and export quantities.

These datasets were merged and aggregated to generate a new dataset containing, for each country and each year, the following indicators:

- Total cement imports;
- Total cement exports; and
- Total available production capacity.

Historical cement consumption (interpreted as demand) was estimated using an assumed capacity utilisation rate, U, based on industry averages, typically ranging between 70–80% (Jaganmohan, 2024). The specific value used in the model is set to 75%. The estimated consumption for each country and year is calculated as:

$$\text{Consumption}_{it} = \text{Imports}_{it} + (\text{Capacity}_{it} \times U) - \text{Exports}_{it},$$

Where:

- Consumption_{it} is the estimated cement consumption in country i in year t;
- Imports_{it} and Exports_{it} represent the aggregated import and export data for country i in year t;
- Capacity_{it} is the total cement production capacity available in country i in year t; and
- U is the assumed utilisation rate of the production capacity.

These processed data form the basis for estimating future demand. The following section discusses the forecasting methodology used and how the resulting projections are prepared as input for the optimisation model.

5.2 Forecasting

Accurate forecasting of future cement demand is a critical component of the optimisation model developed in this research. The model aims to optimise both investment and distribution decisions within the cement industry supply chain. To make informed decisions effectively, reliable long-term forecasts of cement demand at a country-specific level are necessary.

To identify the most suitable forecasting model, multiple approaches were considered: Holt-Winters Exponential Smoothing, ARIMA, Prophet, and deep learning methods. Holt-Winters and ARIMA, though reliable for short-to-medium-term horizons and simple trends (Box et al., 2015; Hyndman & Athanasopoulos, 2018), exhibit limitations when forecasting nonlinear patterns and structural shifts in long-term data (Lekkala, 2024). Furthermore, according to Lekkala (2024), deep learning approaches, although powerful for capturing nonlinearities and complex dependencies, were less suitable due to their computational intensity, lower interpretability, and dependency on larger datasets.

Considering these constraints, Prophet emerged as the most appropriate forecasting approach. The Prophet effectively handles long-term forecasting horizons by explicitly modelling (non)linear growth curves, aligning with the observed trends in cement demand (Lekkala, 2024; Taylor & Letham, 2018). Its intuitive additive model structure, which decomposes forecasts into trends and seasons (when applicable), ensures interpretability and transparency in forecasts.

5.2.1 Data Preparation and Outlier Treatment

To prepare the dataset for forecasting, yearly country-level data from 1995 to 2023 were compiled, including cement import and export quantities, production capacities, and estimated consumption values. Missing import or export data were treated as zero, assuming no trade occurred in those years.

To ensure robust forecast performance, outlier detection was applied using two standard methods: the Z-score method and the IQR method. The Z-score method identifies values that lie more than three standard deviations from the mean, assuming an approximately normal distribution Kolbaşi and Ünsal (2015). The IQR method, on the other hand, is a non-parametric technique that detects outliers as those falling below the first quartile minus 1.5 times the IQR or above the third quartile plus 1.5 times the IQR (R. Wang & Gong, 2025). Outlier detection and interpolation were performed separately for each country's time series over the 1995–2023 period to ensure consistency within national demand trends. Both methods were implemented and compared based on forecasting accuracy, as reported in the section 5.3. All identified outliers were replaced using linear interpolation.

5.2.2 Forecast Model Configuration and Scenario Setup

Prophet was configured with and without the logistic growth setting. The forecasted demand is subsequently spatially disaggregated to the top three most populous cities in each country to improve spatial realism for the distribution model. Only the central estimates (median forecast) are used as input to the optimisation model. Although Prophet also produces lower and upper confidence bounds, these are not used to define demand scenarios. This is because the model focuses on a single supply chain belonging to a single company, whereas the forecast reflects global demand. It is assumed that, even under conservative demand growth, total global demand will remain higher than the supply chain's capacity to meet. Therefore, using demand scenarios would likely not affect the model's decisions and is not considered necessary in this case.

5.3 Validation

To validate the forecasting model, a train-test split was applied. The model was trained on data from 1995 to 2017 and tested from 2019 to 2023. This split enables out-of-sample evaluation, thereby increasing the credibility of the forecasts.

To assess forecast accuracy, the MAPE was calculated. According to Lewis (1982), MAPE values below 10% indicate highly accurate forecasts, while values between 10–20% are considered good and values between 20–50% are considered reasonable forecasting. The majority of country-level forecasts in this study fall within the 10–20% range, indicating a reasonable level of reliability. Table 5.1 presents the average MAPE and number of countries with a MAPE below 50%, comparing the performance of the Z-score and IQR outlier handling methods, both with and without the logistic growth configuration.

Table 5.1: Comparison forecast results.

growth='logistic'	**Method**	**Average MAPE**	**Nr countries (MAPE $\leq$ 0.50)**
No	Z-score	0.129	177
No	IQR	0.124	190
Yes	Z-score	0.130	181
Yes	IQR	0.119	188

These processed forecasts serve as a key input for the optimisation model, with the configuration yielding the lowest average MAPE score being selected to inform distribution planning decisions.

In conclusion, this chapter presented a comprehensive forecasting approach for long-term cement demand tailored to the needs of the optimisation model. Through systematic data preparation, robust outlier handling, and validation using historical data, demand forecasts are sufficiently accurate and reliable. These demand estimates serve as a critical foundation for modelling the TP.

The next chapter introduces the mathematical formulation of the optimisation model. This model integrates the demand forecasts developed here with key economic and environmental parameters, as discussed in chapter 3 and chapter 4 to determine optimal investment and distribution strategies under various policy scenarios.

Chapter 6

Mathematical Model

Note on this chapter: Portions of this chapter are drawn from the manuscript "Optimising Cement Supply Chain Investment and Distribution Decisions Under The CBAM: An Integrated MILP Decision Framework", authored by Karthaus (2025), currently submitted for publication. The manuscript presents a concise account of the methods and core results; this chapter, along with the following one, builds upon that foundation by providing additional background and more extensive data analyses.

This chapter presents the mathematical optimisation model developed to support investment and distribution decision-making in the cement supply chain under evolving climate policy regimes. Specifically, the model addresses the third sub-question.

To answer this, a MILP framework is formulated that integrates investment decisions in carbon capture technologies with distribution planning, optimising overall profit. By capturing the interdependencies between capital investments and logistics planning, the model provides a decision-support tool that can evaluate cost-effective decarbonisation strategies. The mathematical model developed in this chapter serves as the basis for the scenario analyses in the subsequent chapter, where the impact of various carbon policy trajectories on global cement trade patterns and mitigation outcomes for emissions is assessed.

6.1 Model Description

In this chapter, the mathematical model developed to optimise investment and distribution decisions in the cement industry supply chain is presented. The model builds upon the TP, a well-known optimisation problem that seeks to determine the optimal distribution of a product from supply nodes to demand nodes while minimising transportation costs (arc costs) and ensuring supply and demand constraints are met (Hitchcock, 1941). In the context of this thesis, the supply nodes represent cement production plants, while the demand nodes represent cities. The costs of the arcs will include production costs, transportation costs, and costs related to carbon emissions, with the cost of investment modelled at the supplier nodes.

The problem is formulated as a MILP model with two key decision variables. The distribution decision variable is indicated by x_{ijte}. It represents the quantity of cement in tons transported from production plant i to demand region j at time step t, and e indicates whether it is cement without carbon capture or one of the carbon capture technologies. This variable is modelled as continuous.

For the strategic decision, a binary variable y_{iet} is modelled. It indicates whether a technology e is chosen at plant i at time step t. In the set of technologies lies also the option of staying with the current production (baseline).

The investment and distribution decisions are interconnected, as the choice to invest in carbon reduction technology at a plant affects the cost structure of the modelled arcs. The assumption in this model is that decisions are made under perfect foresight, meaning that the impact of an investment on future operational decisions is fully known at the time of decision-making. This assumption allows for the formulation of an integrated model that simultaneously optimises both investment and distribution decisions.

The remainder of this chapter is structured as follows. In subsection 6.1.1, the fundamental components are presented. This includes the sets, parameters, and variables of the model. In section 6.2, the mathematical model is discussed.

6.1.1 Models Components

To formulate the optimisation model, it is essential to define the fundamental components of the model. This section presents the sets, parameters, and decision variables that structure the mathematical model.

The sets define the structural elements of the model, such as production facilities, demand nodes, and investment technologies. The parameters represent fixed input data that influence decision-making, including production capacities, carbon prices, and emission factors. Some of the parameters are time-dependent. Lastly, the model incorporates decision variables. The decision variables capture the distribution and investment decisions being made.

The subscripts denote the dimensions of the decision space: i refers to individual production facilities (set F), j to demand nodes (set D), t to discrete time periods over the 2025–2050 planning horizon (set T), and e to technology alternatives (set E), specifically baseline (B), post-combustion (P), or oxy-fuel (O) carbon capture options.

The model's parameters can be grouped into four categories. First, capacity and timing parameters (cap_i, μ_e) define each plant's annual throughput and retrofit lead time. Second, cost parameters (ρ_{ie}, τ_{ij}, ψ_{iet}, σ_{ijet}, ζ_{ie}, λ_e) capture all per-unit production, transport, emissions, CBAM levy, storage and investment costs. Third, market and demand parameters (q_{jt}, Q_{tot}, β_c, δ_j) specify customer requirements, total industry demand, historical market-share caps, and tax-deductibility rules. Finally, revenue parameters (π_{jt}) denote the unit selling price at each demand node.

The complete list of sets, parameters, and variables, including their mathematical notation, domains, and units, is provided in Table 6.1.

6.2 Model Formulation

In this section, the mathematical formulation of the optimisation model is discussed. The objective function is first introduced, followed by a detailed presentation of the model constraints. To enhance clarity, the constraints are categorised based on their function within the model, with explanations provided after each group.

6.2.1 Objective Function

The objective function maximises total profit over the planning horizon, considering revenues, transportation costs, production costs, emission-related costs, CBAM costs, and investment costs:

$$\max \quad \sum_{i\in F}\sum_{j\in D}\sum_{t\in T}\sum_{e\in E}(\pi_{jt}-\rho_{ie}-\psi_{iet}-\sigma_{ijet}-\tau_{ij}-\zeta_{ie})x_{ijte}-\sum_{i\in F}\sum_{e\in E}\lambda_{ie}\, y_{ieT^{Max}} \tag{6.1}$$

Profit is calculated by first summing the revenue generated from fulfilling customer demands, which is derived by multiplying the sales price at each customer location by the quantity of cement delivered to that location. From this revenue, several costs are deducted: transportation costs, reflecting expenses incurred to move cement from suppliers to customers; production costs (ρ_{ie}), which vary depending on the supplier and the investment option selected; emission-related costs (ψ_{iet}), accounting for costs linked to emissions resulting from production under various technology scenarios and periods; the costs of transporting and storing carbon after it is captured (ζ_{ie}); and the CBAM-related charges (σ_{ijet}), reflecting

Table 6.1: Definition of sets, parameters, and decision variables used in the optimisation model.

Symbol	Parameter	Domain	Unit	Reference
Sets and indices				
F	Set of cement production facility nodes	$i \in F$		
D	Set of demand nodes	$j \in D$		
T	Planning horizon ($T = \{T^{Min}, ..., T^{Max}\}$)[a]	$t \in T$		
E	Set of carbon capture technologies and baseline option ($E = \{\mathrm{B}, \mathrm{P}, \mathrm{O}\}$)[b]	$e \in E$		
Parameters				
β_c	Maximum historical share of total cement shipments to region c	$0 \leq \beta_c \leq 1$	[fraction]	section 7.1
Θ	Maximum annual investment budget	$\Theta \in \mathbb{R}^+$	[$/year]	section 7.1
cap_i	The yearly production capacity available per production plant ($\mathrm{cap}_i = C_{\mathrm{B}i} + C_{\mathrm{P}i} + C_{\mathrm{O}i}$)	$\mathrm{cap}_i \in \mathbb{R}^+$	[ton]	Appendix C
$\mathrm{Q_{tot}}$	Total annual production capacity of all the production facilities	$\mathrm{Q_{tot}} \in \mathbb{R}^+$	[tons/year]	Appendix C
μ_e	Time needed for retrofit the production facility	$\mu_e \in \mathbb{N}^+$	[years]	subsection 4.1.5
τ_{ij}	Transportation cost per ton cement	$\tau_{ij} \in \mathbb{R}^+$	[$/ton]	section F.2
ρ_{ie}	Production costs for one ton cement	$\rho_{ie} \in \mathbb{R}^+$	[$/ton]	Appendix G
ψ_{iet}	Cost of emissions from facility's region per ton cement	$\psi_{iet} \in \mathbb{R}^+$	[$/ton]	section A.1
σ_{ijet}	Net CBAM charge per ton of cement	$\sigma_{ijet} \in \mathbb{R}^+$	[$/ton]	
ζ_{ie}	Transport and storage cost per ton cement	$\zeta_{ie} \in \mathbb{R}^+$	[$/ton]	Appendix D
λ_e	Capital cost of investment	$\lambda_e \in \mathbb{R}^+$	[$]	Appendix G
δ_j	Whether paid carbon taxes in production region are deductible in the demand region	$\delta_j \in \{0,1\}$	[binary]	
q_{jt}	Demand of the customer	$q_{jt} \in \mathbb{R}^+$	[tons/year]	chapter 5
π_{jt}	Revenue for 1 ton of cement at customer	$\pi_{jt} \in \mathbb{R}^+$	[$/ton]	section G.1
Variables				
x_{ijte}	Amount of cement distributed	$x_{ijte} \in \mathbb{R}^+$	[ton]	
y_{iet}	Indicates the active technology	$y_{iet} \in \{0,1\}$	[binary]	

[a] The model considers a 25-year planning horizon starting in 2025, such that $T^{\mathrm{Min}} = 2025$ and $T^{\mathrm{Max}} = 2050$.
[b] The elements of set E represent the following investment options: B — baseline case without carbon capture; P — investment in post-combustion carbon capture; O — investment in oxy-fuel combustion carbon capture.

the cost burden for carbon-intensive imports into regulated markets. Finally, investment costs for carbon capture technologies selected by suppliers (represented by $y_{ieT^{Max}}$) are also subtracted. The objective, therefore, balances all relevant cost components against revenue to determine the optimal investment and distribution strategy.

6.2.2 Constraints

This subsection presents the set of constraints that govern the feasible region of the optimisation model. The constraints are grouped by thematic purpose. Specifically, they enforce production capacity restrictions, demand restrictions, investment constraints, annual budget caps, technology deployment timelines, and market share limitations. Each group of constraints is introduced with a short explanation to clarify its role within the overall modelling framework.

Production capacity constraints:

$$\sum_{j\in D} x_{ij,2025,\mathrm{B}} \;\leq\; C_{\mathrm{B}i} \qquad \forall\, i \in F \tag{6.2}$$

$$\sum_{j\in D} x_{ij,2025,\mathrm{P}} \;\leq\; C_{\mathrm{P}i} \qquad \forall\, i \in F \tag{6.3}$$

$$\sum_{j\in D} x_{ij,2025,\mathrm{O}} \;\leq\; C_{\mathrm{O}i} \qquad \forall\, i \in F \tag{6.4}$$

$$\sum_{j\in D} x_{ijte} \leq \mathrm{cap}_i y_{i,e,t} - \mathrm{cap}_i \mu_e \big(y_{iet} - y_{iet-1}\big) \qquad \forall\, i \in F,\; e \in E,\; t \in T \setminus \{T^{Min}\} \tag{6.5}$$

Constraints (6.2)–(6.4) enforce initial capacity limitations, ensuring that in the base year (2025), production is restricted to technologies for which capacity already exists. Constraint (6.5) generalises this rule across future years: it prevents dispatch unless the technology is activated and enforces downtime penalties during retrofitting. The parameter μ_e captures technology-specific downtime, typically zero for baseline and post-combustion options and one for oxy-fuel technologies that require shutdown for a year (as discussed in subsection 4.1.5).

Demand constraints:

$$\sum_{i\in F}\sum_{e\in E} x_{ijte} \leq q_{jt} \quad \forall j \in D, t \in T \tag{6.6}$$

Constraint (6.6) ensures that the total cement delivered to each demand node does not exceed its known demand in any period.

Investment logic constraints:

$$y_{iet} - y_{ie,\,t+1} \leq 0 \quad \forall i \in F, e \in E \setminus \{\mathrm{B}\}, t \in T \setminus \{T^{Max}\} \tag{6.7}$$

$$\sum_{e\in E} y_{iet} = 1 \quad \forall i \in F, t \in T \tag{6.8}$$

$$y_{i\mathrm{O}t} = 0 \quad \forall i \in F, t \in T : \; t < 2030 \tag{6.9}$$

These constraints define the investment dynamics within the model. Constraint (6.7) enforces irreversibility, preventing technologies from being reversed once adopted. Constraint (6.8) ensures mutual exclusivity by requiring exactly one technology option – baseline, post-combustion, or oxy-fuel – to be active at each site and time. This assumption is considered realistic because, once a cement producer undertakes the substantial investment required for carbon capture technology, it is economically rational to operate the plant using the installed technology to recover the investment costs; operating without it would forgo expected savings on carbon liabilities. Constraint (6.9) further specifies that oxy-fuel combustion technologies cannot be adopted before 2030, aligning with technological readiness timelines reported in the literature (Hills et al., 2016).

Investment budget constraints:

$$\sum_{e \in E} \sum_{i \in F} (y_{iet+1} - y_{iet}) \lambda_e \leq \Theta \quad \forall t \in T \setminus \{T^{Max}\} \tag{6.10}$$

This constraint limits annual investment outlays to not exceeding the available budget Θ, summing only new investment commitments year by year.

Regional market share constraint:

$$\sum_{i \in F} \sum_{j \in D_c} \sum_{e \in E} x_{ijte} \leq \beta_c \, Q_{\text{tot}} \quad \forall c \in \mathcal{C}, t \in T \tag{6.11}$$

Here, $\mathcal{C}$ is the set of continents, and D_c denotes the subset of demand nodes in region c. This constraint restricts the share of total cement volume that can be delivered to each continent to a calibrated maximum share β_c. These limits reflect realistic trade constraints and market competition assumptions based on historical trading patterns, preventing implausible overconcentration of supply in cost-favourable regions.

This chapter has presented the mathematical formulation of the optimisation model developed to support investment and distribution decision-making in decarbonising the cement supply chain. The model integrates investment choices in carbon capture technologies with distribution decisions across global markets while accounting for carbon pricing policies such as the CBAM. Key elements of the model include technology-specific production costs, emissions-related costs, retrofit downtimes, and annual investment budgets. The objective function maximises cumulative profit by balancing revenues against a wide range of operational and environmental costs. A set of constraints ensures physical feasibility, investment logic, policy compliance, and realistic market behaviour. This integrated MILP framework serves as the analytical foundation for the scenario and sensitivity analyses that follow in the subsequent chapter.

Chapter 7

Results

This chapter evaluates the effect of the CBAM through a series of scenarios and sensitivity analyses applied to the Heidelberg Materials case study. The model is executed under two policy scenarios: one with the CBAM regulation active and one without. The activation of the CBAM is simulated by including or excluding the CBAM-related cost component in the objective function. These two cases are compared in terms of the number of investments in carbon capture technologies and shifts in distribution flows.

This thesis does not extensively analyse the individual terms of the objective function – such as transport costs, production costs, carbon costs, or investment costs – because the primary research interest lies in understanding how regulatory frameworks, particularly the CBAM, influence optimal investment locations and distribution strategies in the cement supply chain. Rather than comparing absolute cost components, the focus is on how these decisions shift under different policy scenarios. Moreover, since the cost terms are deterministic and mostly modelled consistently across scenarios, their values provide limited additional insight beyond what is already captured in the flow and investment outcomes.

Because the distribution results are presented in absolute quantities, the height of each bar is subject to two key modelling assumptions. First, market share constraints limit the maximum proportion that any supplier region can serve, so volumes cannot exceed these limits. Second, this thesis does not consider the construction or acquisition of new production capacity; all supplier output is therefore constrained by existing capacity over the 25-year horizon. Together, these assumptions impose a hard ceiling on the bar-chart values, explaining why volumes plateau in certain years.

This chapter is structured as follows. It begins with a section presenting the Heidelberg Materials case study, which contextualises the model's application and frames the results. Following this, the effect of the CBAM under the STEPS scenario is discussed. The STEPS scenario is considered the base case and is used as a benchmark for the sensitivity and scenario analyses. The following section presents the sensitivity analysis results, and finally, the outcomes for the APS and NZE carbon pricing pathways are examined.

7.1 Case Study: Heidelberg Materials

While the model described in this chapter is designed to be general, it is instantiated and tested using Heidelberg Materials as a case study. This company was selected for its global footprint, publicly stated decarbonisation goals, and early adoption of carbon capture technologies, which make it a representative and data-accessible benchmark in the cement sector.

To reflect this application, several model elements incorporate data specific to Heidelberg Materials. The set of supply nodes F corresponds to the company's known cement production facilities. Regional market shares (Equation 6.11) are calibrated using Heidelberg Materials' annual fact sheets (Heidelberg Materials, 2023, 2024b, 2025). In this constraint, regional shipment shares β_c are set to the highest observed proportion of global deliveries per continent from 2021 to 2024, thereby constraining future flows to realistic levels while allowing moderate reallocation.

Moreover, Heidelberg Materials' existing investment in post-combustion carbon capture at its Porsgrunn facility is explicitly included in the model. This is enforced through constraint (7.1), which fixes the investment decision variable $y_{i\mathrm{P}t}$ to one for that specific node and technology over the entire planning horizon. The corresponding capital cost is excluded from the objective function for this investment, as it is assumed to have already been incurred.

$$y_{\mathrm{PorsgrunnP}t} = 1 \qquad \forall\, t \in T \tag{7.1}$$

Finally, the annual investment budget Θ is based on Heidelberg Materials' reported expenditures on cement-related property, plant, and equipment in 2024 (Heidelberg Materials, 2024a). While many cost parameters, such as production, transport, and carbon storage, are drawn from broader literature, these company-specific adjustments enable the model to simulate realistic decisions under regulatory and economic constraints that Heidelberg Materials is likely to face.

This application contextualises the model's structure and supports the scenario and sensitivity analyses presented in the following sections.

7.2 Scenario STEPS

Under the STEPS scenario, baseline investment and distribution patterns are established before any CBAM implementation. By contrasting outcomes "without the CBAM" against those "with the CBAM", this section isolates how the CBAM modifies both the location of carbon capture investments and the flow of cement volumes into Europe. First, the investment decisions for carbon capture are examined. Next, distribution decisions are analysed with a particular focus on Europe's market share, illustrating how the CBAM alters sourcing from Africa, Asia, North America and domestic producers. The section concludes with a series of heatmaps that detail, at intervals, the magnitude and direction of trade-flow changes induced by the CBAM.

Throughout this analysis, the assumption of perfect foresight underpins all modelled decisions, implying that investors fully anticipate future carbon prices, phase-outs of free allowances, and other carbon pricing mechanisms. Such an assumption ensures a clear comparison of economic incentives across regions but also represents a limitation when contrasting with real-world uncertainty. By establishing the STEPS baseline in this manner, subsequent sensitivity and scenario analyses can build upon a coherent narrative, ultimately leading to industry- and policy-relevant insights. Additional figures and details of the results can be found in section H.1.

7.2.1 Investment Decisions STEPS

Under the STEPS scenario assumptions, no new carbon-capture investments become economic unless the CBAM is in force[1]. However, once the CBAM is applied – effectively imposing an "equivalent" ETS levy on imports – carbon capture retrofits in low-cost production regions become economically viable.

Excluding Heidelberg Materials' post-combustion retrofit in Norway (which was already operational before 2025), the model identifies ten new carbon-capture sites under STEPS and active CBAM regulation. These plants are mainly located around South Asia, plus two nearer to Europe in Central Asia and two in Southeast Asia: Aleksinsky District (2035), Bachaoli Khurd (2034), Chittagong (2036), Cirebon

[1] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

(2031), Donda Padu (2033), Kotabaru Regency (2029), Narayanganj District (2030), Narsinghgarh (2032), Puzhuthivakkam (2028), Slantsy (2038), and Tumkur (2037).

These ten locations (mapped in Figure 7.1) cluster heavily in Asia. No European country hosts new capture projects, highlighting that production costs in traditional EU markets remain too high to justify retrofit without additional support.

Figure 7.1: Geographic locations of the investments made under the STEPS scenario.

Figure 7.2 presents a subregional breakdown of these investments as stacked bars – each pair comparing "with the CBAM" (left bar) to "without the CBAM" (right bar). Under the STEPS scenario without the CBAM, every subregion's bar remains unfilled (no new projects). Once the CBAM is active, South Asia accounts for seven of ten retrofits (five in India, two in Bangladesh), Southeast Asia adds two (Indonesia), and Western Russia contributes the remaining two.

In all cases, low production-cost differentials drive location choices. Even when factoring in carbon prices and transport to Europe, cement produced with carbon capture in Asia remains more cost-competitive than an EU-based retrofit would be under STEPS pricing[2].

By concentrating new investments entirely in Asia once the CBAM is implemented, the model illustrates how such a regulation can redirect capture incentives to regions where per-ton production costs are minimal. This outcome suggests that the absence of any European retrofits under STEPS and the CBAM regulation indicates that the CBAM alone does not incentivise the decarbonisation goal of Europe. To encourage domestic capture in the EU, targeted policy measures may be necessary.

7.2.2 Distribution Decisions STEPS

Figure 7.3 presents the STEPS scenario distribution outcomes without the CBAM, combining a line plot of regional flow shares and a stacked bar breakdown of Europe's supply sources. In the line plot (Figure 7.3(a)), each solid curve represents the percentage of total cement distribution allocated to one of four regions – Europe, Africa, Asia, and North America – relative to overall production capacity. Dotted lines on the same axis trace the evolution of carbon prices, where the phase-out of free allowances in the

[2]Figures in section H.4.2 confirm that even a 20% increase in transportation costs fails to shift retrofits back to Europe under the CBAM.

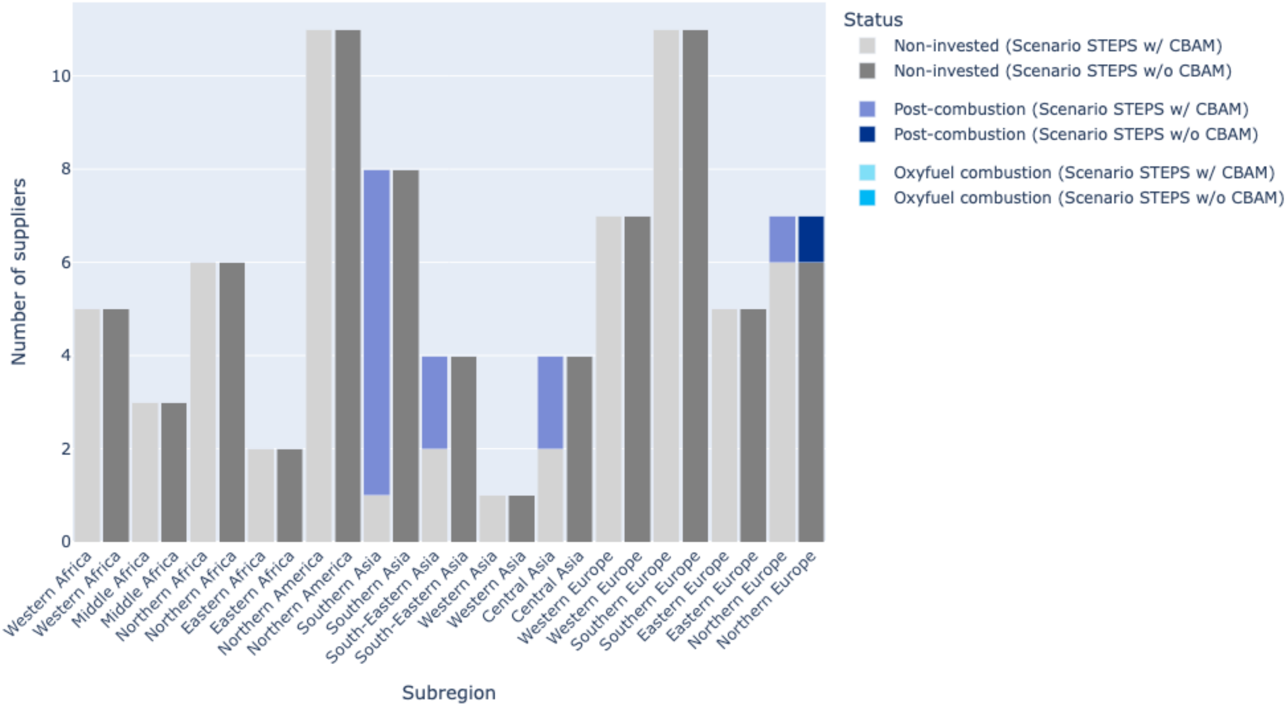
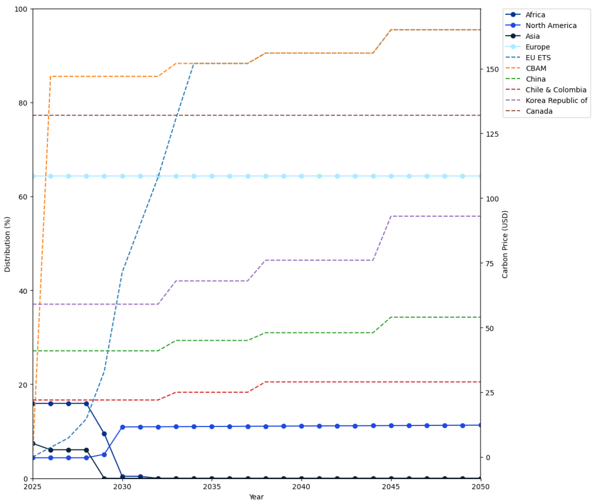


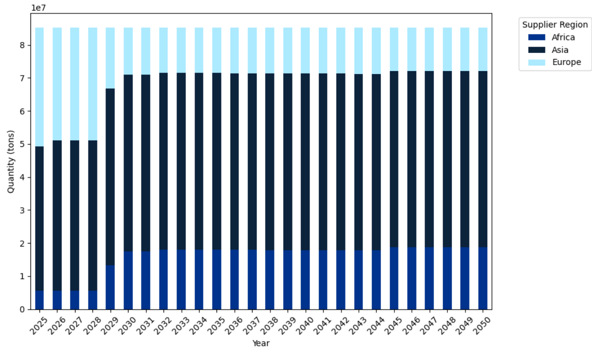
Figure 7.2: Comparison of investments made with or without the CBAM in the different subregions under the STEPS scenario.

EU ETS is visible. Because the model enforces market-share caps and does not consider newly built plants in this study, distribution to Europe often operates at its maximum allowable level. Between 2025 and 2030, Europe's share remains the same; meanwhile, Asia's share steadily declines from nearly 20 per cent to zero. During the same interval, Africa's share also dips, while North America absorbs a growing portion of redirected volumes.

The adjacent bar chart (Figure 7.3(b)) illustrates how Europe's internal demand is allocated among supplier regions. Between 2025 and 2028, virtually all European consumption comes from domestically produced cement, reflecting still-low effective carbon costs under (partial) free allowances. Beginning in 2029, as those allowances enter their steepest decline, Asian and African-produced cement makes its first significant inroads into the European market, being more profitable. This increased profitability arises because the steep reduction in EU ETS allowances significantly raises the carbon cost burden on European producers (mostly without carbon capture), thereby increasing the estimated revenue margin within this region (see section G.1). While production costs in Africa and Asia remain relatively stable during this period, the rising carbon costs in Europe widen the profit gap in favour of these external regions. As a result, the model reallocates distribution flows toward imports from Africa and Asia to meet European demand more cost-effectively. After 2030, the distribution remains uneven, with a slight decline in Europe's share in the later years. This trajectory indicates that, in the absence of the CBAM, cost-advantaged exporters fully exploit the window created by the EU ETS phase-outs, leaving European-produced cement with only a marginal market share after the phase-out of free allowances.



(a) Regional flow shares and carbon-price evolution (no CBAM).

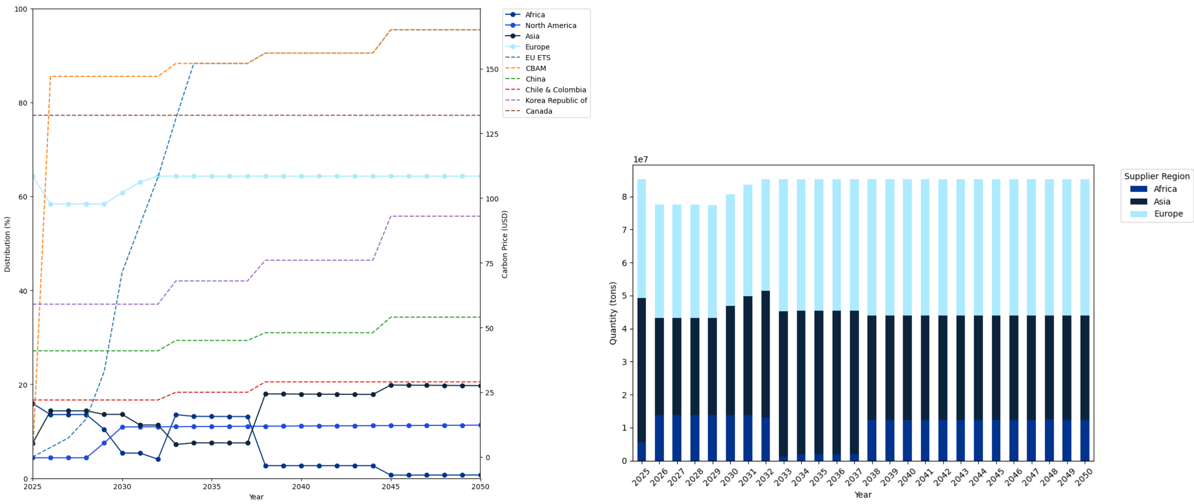


(b) Europe's supply sources by region (no CBAM).

Figure 7.3: Distribution under STEPS without the CBAM. The line plot shows each region's percentage of total distribution (summing to 100% when capacity is fully utilised), with dotted lines indicating the EU ETS price and free allowance phase-outs. The stacked bars display how Europe's domestic demand is met by suppliers from Europe, Africa, Asia, and North America over time.

When the CBAM takes effect in 2026 (Figure 7.4), imported cement into Europe incurs an ETS-equivalent levy, narrowing the cost gap between EU incumbent plants and foreign-produced cement. In the line plot (Figure 7.4(a)), Europe's share remains high but experiences a slight decline with the introduction of the CBAM in the first few years. From 2028 onward, the upward trend resumes, which can be attributed to the first investment made in 2028 becoming operational in 2029, as well as the increasing estimated revenue potential within Europe during this period.

The corresponding bars (Figure 7.4(b)) reveal that under the CBAM, European producers consistently cover a significant share of European demand. The initial increase in the distribution of Asian-produced cement towards Europe is driven by the first carbon capture installations becoming active. Then, in 2038, African-produced cement captured a share of what had been the Asian market. This shift reflects changes in carbon prices across regions: as EU prices rise less than those in the Republic of Korea, Heidelberg Materials optimises by sending more of its Asian output to the Republic of Korea, due to the higher profit margin created there, and rerouting African production into Europe.



(a) Regional flow shares and carbon-price evolution (with the CBAM).

(b) Europe's supply sources by region (with the CBAM).

Figure 7.4: Distribution under STEPS with the CBAM. The line plot shows each region's share of the total distribution alongside the EU ETS price trajectory.

To quantify how the CBAM reshapes trade flows, Figure 7.5 presents six heatmaps – each for 2025, 2030, 2035, 2040, 2045, and 2050 – showing the absolute difference in shipment volumes (million tpa) from each supplier region (rows) to each customer region (columns), comparing "with the CBAM" minus "no CBAM". Blue cells indicate greater shipments under the CBAM; red signifies reduced shipments; white means negligible change.

In 2025 (Figure 7.5(a)), all cells are white since the CBAM does not apply until 2026, and distribution patterns coincide precisely with the no-CBAM case. By 2030 (Figure 7.5(b)), Europe's intra-regional shipments will rise by about 19.5Mt, while Asia's exports to Europe drop by approximately 20.5 Mt, redirecting it mainly to Asia (18.1Mt) and a small amount towards Africa (2.4Mt). Africa shifts its distribution from Europe and North America towards itself. North America registers no changes. This reflects the CBAM's levy, which effectively shifts trade flows.

In 2035 (Figure 7.5(c)), Europe increased its production under the CBAM, while Asia and Africa continued to distribute less to Europe. This indicates that European-produced cement is more competitive with the CBAM in place. Correspondingly, Asia and Africa reroute those volumes chiefly to intra-regional markets. Europe's surplus begins flowing to North America, indicating new export opportunities for EU producers outside their home market. Across 2040–2050 (Figure 7.5(d) and Figure 7.5(f)), these patterns remain stable.

(a) Snapshot year 2025.

(b) Snapshot year 2030.

(c) Snapshot year 2035.

(d) Snapshot year 2040.

(e) Snapshot year 2045.

(f) Snapshot year 2050.

Figure 7.5: Heatmaps of shipment-volume differences (CBAM minus no CBAM) by supplier (rows) and customer (columns) at five-year intervals. Blue values indicate increased shipments under CBAM; red indicates reductions; white indicates negligible change.

Under the STEPS scenario, carbon capture investments by Heidelberg Materials cluster exclusively in low-cost regions once the CBAM is implemented. In the absence of the CBAM, European retrofit projects remain uneconomic; however, the introduction of CBAM in 2026 alters that calculus. South Asian sites, Indonesian facilities, and two locations in western Russia become the only recipients of new carbon capture capital, precisely where Heidelberg Materials can capture and ship cement to Europe most affordably once imports carry an equivalent carbon charge.

Those same cost dynamics also reshape trade flows. Without the CBAM, Heidelberg Materials' European plants will steadily lose their domestic share as the free allowance phase-outs increase carbon burdens; foreign producers will step in to fill the gap, and any diverted volumes will either become unprofitable or redirect to other markets. With the CBAM in place, European production regains its competitiveness within the European market. Across supplier–destination pairings, the CBAM redirects several million tons of volume per year back to domestically produced regions.

Viewed end-to-end, this STEPS scenario analysis reveals a clear, company-level supply chain story for Heidelberg Materials. When the CBAM is absent, low-cost plants in Asia gain prominence and European operations risk marginalisation. Introducing the CBAM counteracts that risk and, by extension, curbs carbon leakage by compelling overseas plants to serve non-European markets or decarbonise further to remain competitive in Europe.

For the cement industry, more broadly, these findings highlight the strategic importance of aligning production, capture, and transport costs with policy design. Heidelberg Materials' investment pattern under STEPS with the CBAM suggests that investing in Europe is not economically viable compared to deploying capital in lower-cost regions. From a policymaker's perspective, two key observations emerge. First, the CBAM improves the competitiveness of European-produced cement compared to a scenario without the CBAM, aligning with the regulation's primary goal of levelling the playing field. Second, however, the model shows that decarbonisation efforts are incentivised mainly outside of Europe, as lower-cost regions attract retrofit investments. In light of this, additional policy measures – such as targeted subsidies or tax incentives – may be necessary to support domestic decarbonisation within the EU, reinforcing the objectives of the EU ETS and encouraging retrofit projects on European soil. To assess whether reduced production costs would indeed attract investments back to Europe and to gauge the robustness of these results under different parameter values, a sensitivity analysis is conducted in the next section.

7.3 Sensitivity Analysis

Sensitivity analysis examines how uncertainty in key cost inputs affects model outcomes by varying each parameter within a plausible range. Given the inherent uncertainty in many model inputs – particularly cost estimates – this process identifies which parameters most strongly influence outcomes and therefore warrants further investigation or data collection (Christopher Frey & Patil, 2002; Lenhart et al., 2002). In this study, four cost parameters are tested: production costs, transportation costs, transport and storage costs, and investment costs. Each parameter is uniformly scaled across all regions. For each cost category, investment decisions under both the no-CBAM and CBAM scenarios are evaluated first, followed by an analysis of how these investment outcomes affect Europe's cement supply shares. This structured approach clarifies which cost inputs most significantly impact the company's global carbon-capture deployment and position in the European cement market.

7.3.1 Production Costs

To assess the robustness of the model's output to uncertainty in production cost estimates, the parameter is scaled by factors of 0.5, 0.8, 1.2, 1.5, and 1.8 at all regional cost inputs. This exercise reveals both how investment location choices and Europe's cement supply shares respond to substantial cost fluctuations.

The results are presented first in terms of strategic investment decisions[3] and thereafter in terms of distribution outcomes. Figures and additional details of the results are provided in subsection H.4.1 (Figure H.4 and Figure H.5 for investments; Figure H.7 and Figure H.7 for distribution).

Investment Decisions

Table 7.1 summarises how scaling production costs affects the optimal geographic allocation of carbon capture investments. This analysis reveals critical insights into the drivers of retrofit feasibility and illustrates the contrasting dynamics between scenarios with and without the CBAM regulation.

Table 7.1: Sensitivity of investment decisions to production cost variations.

Cost factor	Investments without the CBAM	Investments with the CBAM
0.5	Five post-combustion retrofits become economically viable: one in Eastern Europe, two in Western Europe, and two in Northern Europe alongside the existing Northern Europe facility.	Additional capture sites emerge in Northern Africa and Northern Europe relative to the base scenario, and several projects in Southern Asia are reallocated to Eastern Europe, Southern Europe, and Western Europe.
0.8	Two post-combustion retrofits are added in Northern Europe in addition to the existing facility.	Both Northern Africa and Northern Europe gain two retrofits each, while all original investments in Southern Asia remain unchanged.
1.2	No new investments are undertaken, matching the base-case outcome.	The number of Southern Asia facilities declines relative to the base case.
1.5	No new investments are undertaken, matching the base-case outcome.	Only one retrofit remains in South-Eastern Asia and one in Southern Asia.
1.8	No new investments are undertaken, matching the base-case outcome.	No new capture facilities are economically feasible.

When the CBAM is not applied, the investment outcomes show a sensitivity to changes in production costs when compared to the baseline case. At a factor of 0.5, several additional retrofits become economically viable relative to the baseline, with new projects appearing in Eastern Europe, Western Europe, and Northern Europe. This expansion highlights that substantial cost reductions alone can make retrofits financially attractive even in the absence of the CBAM. At a factor of 0.8, two retrofits are added in Northern Europe compared to the baseline, indicating that more moderate cost reductions can also unlock additional investment opportunities in traditionally higher-cost European regions.

Conversely, as production costs increase to factors of 1.2, 1.5, and 1.8, no new capture facilities become viable relative to the baseline, and the investment portfolio remains unchanged, with only the single baseline retrofit in Northern Europe. This lack of investment expansion under higher cost factors is expected, as no other factor in the model changes.

The complete set of bar charts for the no-CBAM sensitivity scenarios is provided in Figure H.4. These results demonstrate that, in the absence of a carbon border levy, production cost variations primarily affect the magnitude of investment in Europe, without significantly altering the global cement distribution flows.

[3] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

When the CBAM is applied, the investment pattern diverges from the baseline case. At a factor of 0.5, multiple new retrofits become economically viable compared to the baseline, with additional capture sites emerging in Northern Africa and Northern Europe. Several projects initially planned in Southern Asia are reallocated to Eastern Europe, Southern Europe, and Western Europe. At a factor of 0.8, both Northern Africa and Northern Europe each gain retrofits compared to the baseline scenario, while investments in Southern Asia remain unchanged from their baseline levels. As production costs increase to a factor of 1.2, the number of retrofits in Southern Asia declines relative to the baseline, indicating growing economic infeasibility in that region. When costs rise further to factors of 1.5 and 1.8, the investment portfolio contracts significantly compared to the baseline: at factor 1.5, only one retrofit inSoutheast Asia and one in Southern Asia remain viable, while at factor 1.8, no new projects are initiated, as this scenario yields a less favourable profitability outcome.

The complete set of CBAM-scenario bar charts illustrating these investment shifts is provided in Figure H.5.

The key effects on investment decisions are summarised in the tornado diagrams (see Figure 7.7 and Figure 7.6), which show the deviation in cumulative investments across regions at the end of the planning horizon relative to the base case.

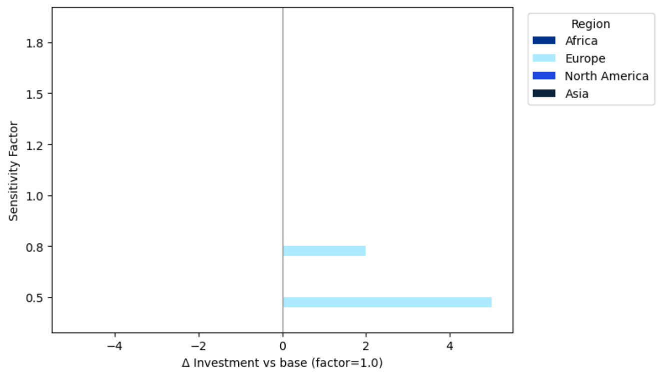


Figure 7.6: Sensitivity of regional investment outcomes to production cost variations under the no-CBAM scenario. Bars indicate the change in cumulative investments by region at the end of the planning horizon relative to the baseline case (cost factor = 1.0).

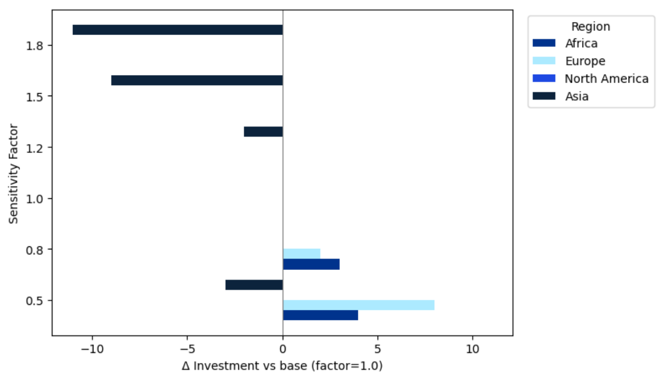


Figure 7.7: Sensitivity of regional investment outcomes to production cost variations under the CBAM scenario. Bars indicate the change in cumulative investments by region at the end of the planning horizon relative to the baseline case (cost factor = 1.0).

Overall, these results demonstrate that under the CBAM, lowered production costs not only facilitate additional investments in traditionally higher-cost regions but also induce a substantial reallocation of projects from Southern Asia toward European and North African subregions. In contrast, without the CBAM, production cost differentials alone only influence the depth of investment within Northern Europe. Notably, while the model reacts to production cost changes, the required cost adjustments to meaningfully shift investment decisions are relatively large, indicating that the model is responsive but not overly sensitive to modest fluctuations. This suggests that the model provides stable and robust investment guidance, with decisions unlikely to swing dramatically based on uncertainties in production cost estimates.

Distribution Decisions

The sensitivity of Europe's cement supply shares to variations in production costs is summarised in Table 7.2.

Table 7.2: Impact of production cost variations on Europe's supply shares.

Cost factor	Supply shares without the CBAM	Supply shares with the CBAM
0.5	No deviation from the base case: Europe's share declines progressively, and lower-cost regions fill the gap.	Europe retains a majority share throughout; African imports initially dip but rebound around 2033 when new capture projects come online, while Asian imports decrease upon the introduction of the CBAM and then partially recover.
0.8	No deviation from the base case: Europe's share declines progressively, and lower-cost regions fill the gap.	Europe's share remains stable; African import volumes fluctuate only marginally, and Asian import patterns drop at the introduction of the CBAM but recover almost as much compared to the base case.
1.2	No deviation from the base case: Europe's share declines progressively, and lower-cost regions fill the gap.	Higher production costs lead to a slight reduction in African imports and a corresponding small increase in Asian imports, but Europe's overall share remains largely unchanged.
1.5	No deviation from the base case: Europe's share declines progressively, and lower-cost regions fill the gap.	Europe maintains a high share; import shares from Africa and Asia shift only marginally compared to factor 1.2.
1.8	No deviation from the base case: Europe's share declines progressively, and lower-cost regions fill the gap.	Under the highest cost factor, Europe's domestic share remains robust; import volumes from Africa decrease slightly, and Asian volumes adjust correspondingly, with no significant change in overall balance.

The sensitivity analysis of Europe's cement supply shares to production cost variations reveals distinct patterns depending on the presence or absence of the CBAM. Under scenarios without the CBAM, scaling production costs across the range of factors from 0.5 to 1.8 produces no observable deviation from the baseline case. Europe's domestic market share declines steadily over time, following the phase-out of free allowances, while imports from lower-cost producers in Africa and Asia progressively fill the supply gap. Even at the lowest cost factor tested, Europe's declining trajectory remains identical to the baseline, highlighting that, without a carbon border levy, cost reductions alone cannot reverse the trend of erosion in Europe's competitive position. These patterns are reflected in the distribution curves shown in Figure H.7, where the slopes remain relatively unchanged across all tested factors relative to the base case.

In contrast, under the CBAM regulations, Europe's domestic market share remains comparatively stable across all production cost factors. At a cost factor of 0.5, European suppliers sustain a dominant market share relative to the baseline, with African import volumes experiencing a temporary decline until around 2033 – corresponding with the commissioning of new carbon capture projects in Northern Africa (Cairo Governorate Desert in 2032 and Tura in 2033) – while Asian imports decrease sharply following the CBAM's introduction and only partially recover thereafter. At higher cost factors (1.2, 1.5, and 1.8), Europe's supply share remains essentially unchanged compared to the baseline, with only minor adjustments: African import shares decrease slightly and Asian volumes increase marginally, reflecting shifts in competitiveness among import sources but without significant impact on Europe's retained market share.

These findings demonstrate that the CBAM alters how production cost variations impact Europe's cement market dynamics. In the absence of the CBAM, changes in production costs, even substantial ones, do not meaningfully affect Europe's declining market share trajectory, which remains vulnerable to competition from low-cost external producers. By contrast, the imposition of the CBAM keeps Europe's market share competitive across all production cost factors. It does have an influence on the market share of Asian- and African-produced cement. Lower production costs increase the African-produced cement distribution towards Europe at the cost of the Asian-produced cement, while increasing costs have the opposite effect.

In summary, scaling production costs by factors from 0.5 to 1.8 reveals that without the CBAM, Europe's market share consistently declines regardless of cost changes, reflecting the dominance of external producers once free allowances are phased out. Under the CBAM, however, lower production costs both stabilise Europe's share and unlock new retrofit investments in Europe and North Africa, while higher costs progressively limit these benefits. This analysis underscores the CBAM's role as a decisive factor in maintaining European supply resilience against global cost disparities.

7.3.2 Transportation Costs

To evaluate how uncertainties in freight rates influence both investment and distribution decisions, all per-unit transportation costs were scaled by factors of 0.5, 0.8, 1.2, 1.5, and 1.8. This approach isolates the effect of transport cost variations on capture investment location choices[4] and on Europe's cement supply shares. Results for investment decisions are summarised in Table 7.3, and distribution outcomes in Table 7.4. Figures and additional details of the results have been located to subsection H.4.2 (Figure H.8 and Figure H.9 for investments; Figure H.10 and Figure H.11 for distribution).

Investment Decisions

Table 7.3 summarises the effect of scaling all transportation cost inputs by factors of 0.5, 0.8, 1.2, 1.5, and 1.8 on the location of carbon capture retrofits, both without and with the CBAM. Across the entire range of multipliers, no deviation from the base case investment pattern is observed: the same set of subregions – identical to those selected at the baseline transport rate – remains optimal under both policy regimes. In other words, whether freight rates are halved or increased by up to 80 per cent, the relative cost

[4] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts. However, it is depicted in the figures for completeness.

competitiveness of each facility is unaffected. Thus, the geographical allocation of new capture projects remains unchanged.

Table 7.3: Sensitivity of investment decisions to transportation cost variations.

Cost factor	Investments without the CBAM	Investments with the CBAM
0.5	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.
0.8	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.
1.2	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.
1.5	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.
1.8	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.	No change relative to the base case: the same subregions are selected for carbon-capture retrofits.

For readers wishing to inspect the subregional bar charts for each multiplier, the corresponding figures have been relocated to subsection H.4.2 (Figure H.8 and Figure H.9).

Distribution Decisions

Table 7.4 presents the effect of scaling transportation cost inputs by factors of 0.5, 0.8, 1.2, 1.5, and 1.8 on Europe's cement supply shares, with and without the CBAM.

When the CBAM is not applied, lower freight rates (factors 0.5 and 0.8) permit African-produced cement to gain a modest foothold in the European market earlier than in the base case, causing Europe's domestic share to decline slightly sooner. Conversely, higher transport costs (factors 1.2–1.8) marginally favour local production as distant suppliers become less competitive. Importantly, the overall downward trend in Europe's share – driven by the phase-out of free emissions allowances – remains intact across all cost multipliers. The detailed time-series charts are provided in section H.4.2 (Figure H.10).

Under the CBAM, Europe's domestic share remains essentially unchanged for all transport cost scenarios (Table 7.4, right column). At the lowest transport cost (factor 0.5), African imports increase marginally, and a small volume of North American cement appears; these import shares recede as transport costs rise, with North American volumes disappearing entirely and African volumes diminishing. Throughout, the CBAM preserves the competitiveness of European producers. In section H.4.2 (Figure H.11), the complete set of the CBAM-scenario distribution curves is presented.

In summary, varying transportation costs have no impact on the locations selected for new carbon capture investments under either the no-CBAM or CBAM regimes. In distribution, lower freight rates modestly accelerate the entry of African imports into Europe when the CBAM is absent, while higher rates favour domestic supply; however, the long-term decline in Europe's share persists once free allowances phase out. Under the CBAM, Europe's domestic market share remains virtually unchanged across all transport cost scenarios, with only marginal fluctuations in import volumes. Thus, transport cost uncertainty plays a

Table 7.4: Sensitivity of Europe's supply shares to transportation cost variations.

Cost factor	Supply shares without the CBAM	Supply shares with the CBAM
0.5	Lowering transport costs results in a modest increase in African-sourced imports into Europe; the European domestic share declines correspondingly slightly earlier than in the base case.	Europe's domestic share remains fully stable; African imports increase marginally, and a small volume of North American cement appears.
0.8	The same pattern holds: reduced freight rates give African producers a modest foothold sooner, while the European share dips slightly earlier.	Europe's share remains constant; African import volumes fluctuate only minimally, and North American volumes vanish.
1.2	European producers hold a slightly larger share as distant suppliers become less competitive; the overall downward trend remains intact.	Under the CBAM, Europe's share continues at the same high level; import shares from Africa and Asia adjust only marginally.
1.5	The European domestic share increases slightly compared to the base case, while African import volumes decline marginally.	Europe retains a stable majority share; African imports decline slightly in the early years and then stabilise.
1.8	At the highest freight rate, Europe's domestic share is marginally larger across all years, with minimal imports from Africa or Asia.	Europe's domestic share remains robust; import volumes from all non-EU regions are minor and stable.

negligible role in strategic investment decisions and only a secondary, limited role in shaping Europe's supply mix.

7.3.3 Transport and Storage Costs

To determine how variations in the per-ton expense of transporting and storing captured carbon influence both investment locations and distribution flows, transport and storage costs were scaled by factors of 0.5, 0.8, 1.2, 1.5, and 1.8. Investment decision outcomes are summarised in Table 7.5, and distribution decision results in Table 7.6. Figures and additional details of the results are provided in subsection H.4.3[5].

Investment Decisions

Table 7.5 summarises the effect of scaling transport and storage costs by factors of 0.5, 0.8, 1.2, 1.5, and 1.8 on the economic viability and location of new carbon capture retrofits under both policy regimes.

When the CBAM is not applied, scaling transport and storage costs across factors from 0.5 to 1.8 produces no change in investment decisions relative to the baseline scenario. Regardless of whether transport and storage costs are reduced or increased, no additional carbon capture retrofits become economically viable. This result highlights that in the absence of the CBAM, variations in transport and storage expenses alone are insufficient to offset the dominant influence of production costs and carbon pricing on investment decisions. The investment landscape thus remains static, with the same retrofit

[5] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

Table 7.5: Sensitivity of investment decisions to transport and storage cost variations.

Cost factor	Investments without the CBAM	Investments with the CBAM
0.5	No change relative to the base case: no new capture facilities become viable.	Two additional retrofits emerge compared to the base case: one in Central Asia and one in Southern Asia.
0.8	No change relative to the base case: no new capture facilities become viable.	One additional retrofit is found in Southern Asia.
1.2	No change relative to the base case: no new capture facilities become viable.	The investment portfolio remains unchanged compared to the base case.
1.5	No change relative to the base case: no new capture facilities become viable.	One fewer retrofit than the base case: the Southern Asia project is no longer viable.
1.8	No change relative to the base case: no new capture facilities become viable.	Two fewer retrofits than the base case: projects in Southern Asia and Central Asia are no longer viable.

portfolio as in the baseline case, underscoring the limited impact of transport and storage costs on triggering new projects in a globally competitive market when the CBAM is inactive.

Under the CBAM regime, however, the analysis reveals a modest but notable sensitivity of investment decisions to variations in transport and storage costs compared to the baseline. At a cost factor of 0.5, two additional retrofits emerge – one in Central Asia and one in Southern Asia – relative to the baseline outcome. At a cost factor of 0.8, a single extra retrofit becomes viable in Southern Asia compared to the baseline. When transport and storage costs increase by a factor of 1.2, the investment portfolio aligns with the baseline configuration, exhibiting no deviation. Further increases to factors of 1.5 and 1.8 reduce economic feasibility: at a factor of 1.5, one Southern Asian project present in the baseline is lost, while at a factor of 1.8, both Southern Asia and Central Asia retrofits are no longer initiated. These results demonstrate that, once the CBAM is in place, transport and storage costs influence the investments made in retrofitting.

The key impacts of these variations on investment outcomes are summarised in the tornado diagram (Figure 7.8), which visualises cumulative investment deviations by region at the end of the planning horizon relative to the baseline scenario. These findings indicate that although transport and storage costs alone cannot unlock retrofits without the CBAM, they become a modifier of investment decisions when the CBAM is active, with relatively significant shifts in these costs determining the viability of one or two additional projects across key regions. This indicates that the model does react to significant changes in the parameter, but is not too sensitive.

These results show that, once the CBAM is in place, variations in transport and storage costs do lead to shifts in retrofit locations – albeit far fewer than observed under production cost sensitivity – reflecting one or two additional or withdrawn projects depending on the cost factor (see subsection H.4.3, Figure H.12 and Figure H.13 for detailed bar charts).

Distribution Decisions

Table 7.6 reports the impact of varying transport and storage costs – scaled by factors of 0.5, 0.8, 1.2, 1.5 and 1.8 – on Europe's cement supply shares, both without and with the CBAM.

When the CBAM is not applied, varying transport and storage costs across factors from 0.5 to 1.8 produce no deviation from the baseline distribution outcome. Because no new carbon capture retrofits

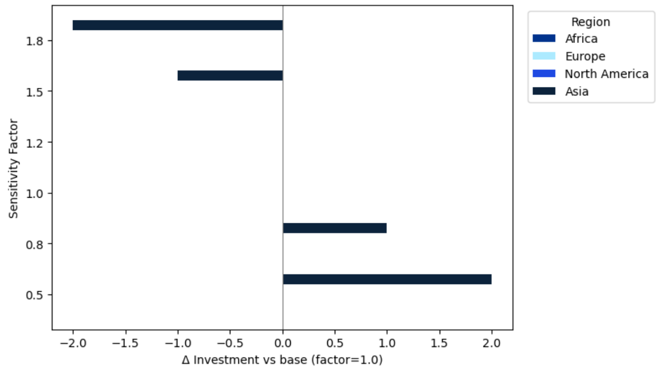


Figure 7.8: Sensitivity of regional investment outcomes to transport and storage cost variations under the CBAM scenario. Bars indicate the change in cumulative investments by region at the end of the planning horizon relative to the baseline case (cost factor = 1.0).

Table 7.6: Sensitivity of Europe's supply shares to transport and storage cost variations.

Cost factor	Supply shares without the CBAM	Supply shares with the CBAM
0.5	Supply shares remain unchanged from the base case, as no new capture facilities are introduced.	Europe's domestic share is stable; Asia's share of imports increases slightly between 2033 and 2037 at the expense of Africa.
0.8	Supply shares remain unchanged from the base case, as no new capture facilities are introduced.	European self-supply remains constant; Asian import volumes edge up modestly mid-decade, with a corresponding slight decrease in African volumes.
1.2	Supply shares remain unchanged from the base case, as no new capture facilities are introduced.	Asia's share of Europe declines marginally over time, while African volumes recover a small portion; Europe's overall share remains roughly the same.
1.5	Supply shares remain unchanged from the base case, as no new capture facilities are introduced.	African imports experience a very slight increase, and Asian imports correspondingly decrease; Europe's domestic share remains approximately constant.
1.8	Supply shares remain unchanged from the base case, as no new capture facilities are introduced.	African import volumes increase minimally, Asian volumes decrease slightly, and Europe's share holds steady.

are made viable under any cost factor without the CBAM, the supply mix to Europe remains constant over time. Europe's domestic market share continues its steady decline as previously observed in the base case, and import shares from Africa and Asia follow identical trajectories to the baseline scenario. These findings indicate that, in the absence of the CBAM, variations in transport and storage expenses alone cannot influence trade patterns or reverse Europe's gradual loss of market share to lower-cost external producers. The stability of these results is evident in the distribution curves presented in Figure H.14, which match the baseline lines across all years and cost factors.

In contrast, under the CBAM implementation, the analysis reveals a subtle shift in import dynamics relative to the baseline. At reduced transport and storage costs (factors 0.5 and 0.8), Asia's share of cement imports into Europe increases slightly around the years 2033 and 2039, as the lower costs, which increase investments made in Asia, make imports from Southern and Central Asia more profitable compared to African sources. Europe's own domestic supply share, however, remains mainly unchanged from the baseline, demonstrating the CBAM's stabilising effect on Europe's competitiveness. As costs rise to factors 1.2 through 1.8, African imports recover a small share of the European market relative to the baseline, as higher transport and storage costs decrease investments made in Asian production plants. This pattern reflects the fact that under the CBAM, changes in transport and storage costs cause a limited number of retrofits to become viable or unviable, leading to modest adjustments in the sources of imports but not to any substantial reshaping of Europe's cement supply structure.

These results demonstrate that while transport and storage cost variations alone do not affect Europe's supply dynamics in the absence of the CBAM, their interaction with the CBAM can subtly influence trade flows by modifying the viability of retrofits in key regions. Nevertheless, the overall distribution remains robust, with only minor fluctuations in import shares between African and Asian suppliers, and no significant impact on Europe's retained market share compared to the baseline.

In summary, varying transport and storage costs by factors from 0.5 to 1.8 show that without the CBAM, Europe's supply mix remains static across all scenarios, reflecting the dominance of production cost and carbon pricing in determining competitiveness. Under the CBAM, small shifts in import shares occur due to one or two retrofits being added or removed in Asia. Still, these changes do not materially affect Europe's domestic market share, underscoring the CBAM's primary role in maintaining Europe's supply stability against fluctuations in logistical costs.

7.3.4 Investment Costs Sensitivity Analysis

Under capital cost sensitivity, scaling the per plant investment expense by factors ranging from 0.65 to 1.35 reflects the ±35% uncertainty associated with cement plant carbon capture costs (Barker et al., 2008). This sensitivity analysis evaluates first how these investment cost variations influence the number and location of new retrofit projects under both policy scenarios[6], and then how the resulting investment patterns affect Europe's cement supply shares under each policy case. Figures and additional details of the results are provided in subsection H.4.4.

Investment Decisions

Table 7.7 presents the effects of scaling the per-plant investment cost by factors of 0.65, 0.80, 1.20, and 1.35 on the geographic distribution of carbon capture retrofits under both policy regimes.

When CBAM is not applied, none of the tested investment cost multipliers yields an additional economic capture facility. The investment portfolio remains identical to the base case in all scenarios (see section H.4.4, Figure H.16).

Under the CBAM, variations in investment costs do alter the set of viable projects, albeit to a lesser extent than seen under production cost sensitivity. At a cost reduction of 0.65, the model replaces one Southern Asia plant with a Southeastern Asia facility. This is also the case for a 0.8 reduction. Increasing by a factor of 1.2 of the baseline cost results in the original investments. Finally, at a 1.35 factor cost increase, all the CBAM-induced capture projects become uneconomic, yielding no new retrofits (see section H.4.4, Figure H.17).

The key effects on investment decisions are summarised in the tornado diagram (see Figure 7.9), which shows the deviation in cumulative investments across regions at the end of the planning horizon.

[6] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

Table 7.7: Sensitivity of investment decisions to investment cost variations.

Cost factor	Investments without the CBAM	Investments with the CBAM
0.65	No change: No new capture facilities become viable.	A Southeastern Asia facility replaces one Southern Asia project.
0.80	No change: No new capture facilities become viable.	A Southeastern Asia facility replaces one Southern Asia project.
1.20	No change: No new capture facilities become viable.	No change: The portfolio remains identical to the base case.
1.35	No change: No new capture facilities become viable.	All base-case CBAM projects are rendered uneconomic, resulting in no new retrofits.

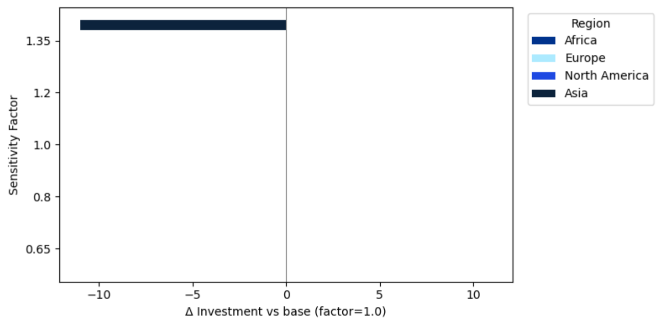


Figure 7.9: Sensitivity of regional investment outcomes to investment cost variations under the CBAM scenario. Bars indicate the change in cumulative investments by region at the end of the planning horizon relative to the baseline case (cost factor = 1.0).

Distribution Decisions

Table 7.8 summarises how scaling the per-plant investment cost by factors of 0.65, 0.80, 1.20, and 1.35 affects Europe's cement supply shares under both policy regimes.

When CBAM is not applied, none of the tested investment cost multipliers yields any new capture facilities, so the network of operating plants remains identical to the base case. Consequently, the distribution of cement to Europe is unchanged across all factors, with domestic and import shares mirroring the reference scenario (see section H.4.4, Figure H.18).

Under the CBAM, shifts in the set of viable retrofits translate into modest changes in import patterns. In the lower-cost scenarios (factors 0.65 and 0.80), only European and Asian facilities supply Europe after the initial years, as African sources lose competitiveness entirely due to the production of more low-carbon cement products in Asia. When capital costs rise above the base case (factor 1.20), the original mix of European, African, and Asian suppliers is restored. Under the highest multiplier (factor 1.35), Asia's export share gradually declines, allowing small volumes of African-sourced cement to reenter the market late in the period. Throughout, Europe's overall domestic share remains broadly stable (see section H.4.4 and Figure H.19).

In summary, scaling investment costs between 0.65 and 1.35 has no impact on capture facility siting when the CBAM is absent, leaving both investments and distribution shares unchanged from the base case. Under the CBAM, a 0.65 and 0.8 reduction in investment costs switches one Southern Asian plant for

Table 7.8: Sensitivity of Europe's supply shares to investment cost variations.

Cost factor	Supply shares without the CBAM	Supply shares with the CBAM
0.65	No new capture facilities emerge, so the distribution mix remains unchanged, mirroring the base case exactly.	After an initial period, only European and Asian plants supply Europe, as African imports lose competitiveness.
0.8	No new capture facilities emerge, so the distribution mix mirrors the base case exactly.	After an initial period, only European and Asian plants supply Europe, as African imports lose competitiveness.
1.20	No new capture facilities emerge, so the distribution mix remains unchanged, mirroring the base case exactly.	Distribution shares revert to the base case: European, African, and Asian suppliers each maintain their original roles.
1.35	No new capture facilities emerge, so the distribution mix remains unchanged, mirroring the base case exactly.	Asian exports to Europe have declined overall but are being offset by African-sourced cement; nonetheless, Europe's share remains roughly constant.

one Southeastern Asian plant. An increase of 1.2 results in the same output as the base case, while a factor 1.35 cost increase renders all the CBAM-induced projects uneconomic. These shifts propagate into Europe's import mix – lower investment costs concentrate supply in Europe and Asia, and higher costs allow modest reentry of African sources – yet Europe's overall domestic share remains broadly stable across all scenarios.

Across the four sensitivity analyses, production cost uncertainty dominates both strategic investment and distribution outcomes. Scaling production costs by between 0.5 and 1.8 triggers multiple shifts in capture investment locations, altering Europe's import mix. New retrofits emerge in Europe, North Africa, and Asia under different policy regimes and cost levels.

By contrast, varying transportation costs with the same factors had no effect on investment siting and only marginally accelerates or retards African imports when the CBAM is absent, while under the CBAM, Europe's domestic share remains roughly unchanged.

Transport and storage costs likewise fail to influence investments without the CBAM and, under the CBAM, induce only one or two additional or withdrawn projects, resulting in tiny shifts in Asia's and Africa's shares of Europe's supply.

Finally, investment cost scaling of ±35% yields no new investments absent the CBAM, and under the CBAM swaps one or two projects among Southern and South-Eastern Asia or, at the highest cost, eliminates all CBAM-induced sites – translating into reconfigurations of Europe's import mix but leaving overall domestic share broadly stable. Together, these results demonstrate that production costs are the primary driver of model outcomes, while the other cost parameters matter mainly under the CBAM and to a much lesser extent.

7.4 Scenario Analysis

Scenario analysis is a vital tool in this study for evaluating how different future policy landscapes may influence strategic decisions in the cement supply chain. Given the long-term nature of investment decisions in carbon capture technologies and the global variation in regulatory environments, it is crucial to examine how shifting carbon pricing trajectories may impact the cost-effectiveness of emissions reduction strategies.

Unlike sensitivity analysis, which assesses model robustness by varying one parameter at a time, scenario analysis enables a more comprehensive examination of alternative future policy conditions, particularly those related to climate legislation and international developments in carbon pricing.

This study incorporates three distinct carbon pricing scenarios derived from the IEA (2024) and discussed in section 4.2. These scenarios encompass a wide range of potential developments in climate policy, taking into account the interaction between carbon pricing and other regulatory measures. This is critical, as carbon pricing rarely functions in isolation – complementary policy measures, such as phase-out plans, influence its effectiveness and implementation.

The base scenario employed in this analysis is the STEPS scenario, which reflects the existing carbon pricing mechanisms, as well as those already announced or scheduled, that, in the eyes of the IEA, are feasible for implementation. The STEPS scenario serves as a conservative benchmark, providing insights into the expected outcomes if governments adhere to their current policy commitments.

The APS and the NZE scenarios represent more ambitious policy pathways. In the APS, higher carbon prices are assumed across regions with net-zero pledges, and several developing countries are projected to adopt new carbon pricing mechanisms. This scenario reflects an increasing political will to meet long-term emissions targets. The NZE scenario represents the most stringent pathway, assuming universal adoption of carbon pricing mechanisms. Here, advanced economies and developing countries with net-zero targets face steep increases in carbon prices, while other developing regions experience smaller, yet rising, price levels.

These three scenarios are selected for analysis due to their direct influence on the relative competitiveness of cement suppliers under the CBAM. Since the CBAM aims to equalise carbon costs between EU producers and foreign exporters, the presence or absence of domestic carbon pricing in exporting countries significantly affects the CBAM-related cost adjustments. By modelling these scenarios, the analysis provides valuable insights into how international policy convergence or divergence could reshape cement trade flows and technology investment decisions.

7.4.1 Scenario APS

Under the APS scenario, which assumes that announced pledges for carbon pricing are implemented according to current policy trajectories, baseline investment and distribution patterns are first established prior to any CBAM enforcement. By contrasting outcomes without the CBAM against those with the CBAM applied from 2026 onward, this section examines how the CBAM affects the geographic allocation of carbon capture investments and alters the flow of cement volumes into Europe. First, carbon capture investment decisions under APS are examined[7]. Next, distribution decisions are analysed with a focus on Europe's market share, illustrating how the CBAM changes sourcing from Africa, Asia, and domestic producers. Finally, a series of heatmaps, updated at five-year intervals, detail the magnitude and direction of trade-flow adjustments induced by the CBAM under APS. Additional figures and details of the results can be found in section H.2.

Investment Decisions APS

Under the APS scenario, carbon capture retrofits become economically viable even before the implementation of CBAM, reflecting APS's more stringent carbon pricing trajectory. In both the "without the CBAM" and "with the CBAM" cases, the model selects ten common retrofit locations. These sites cluster primarily in Asia (seven projects), with two in Europe and one in Canada (Figure 7.10; Figure 7.11).

Notably, absent the CBAM, the model favours European sites beyond the two core projects, presumably to avoid elevated carbon costs under the APS assumptions. In contrast, the introduction of the CBAM

[7] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

Figure 7.10: Geographic locations of the investments made under the APS scenario.

shifts investment toward locations outside Europe that combine low production and transport expenses with the ability to ship into the EU under an equivalent import levy. This contrast illustrates how the CBAM reconfigures the cost calculus: without the CBAM, domestic European retrofits appear comparatively attractive, but once imports face an EU ETS equivalent charge, overseas plants with lower overall per-ton costs are more profitable, even after accounting for transportation to Europe.

In the absence of the CBAM, additional retrofits are predominantly cited in Europe, reflecting APS's elevated EU ETS prices and the progressive reduction of free allowances that narrow the cost differential between domestic capture and imports. Regardless, once the CBAM levies imports at an EU ETS equivalent rate, plants in Southern and Central Asia regain a comparative advantage: their lower production and transport costs offset Europe's higher capture expenses. This dynamic illustrates a potentially perverse outcome of the CBAM: it may shift decarbonisation efforts beyond the EU's borders. As Ambec (2024) cautions, "The CBAM raises new challenges. It should be appropriately designed to level the playing field within and outside the EU, and it has the potential to export decarbonization outside the EU's borders.".

Distribution Decisions APS

Figure 7.12 presents the APS scenario distribution outcomes without the CBAM, combining a line plot of regional flow shares (Figure 7.12(a)) with a stacked bar breakdown of how Europe's demand is met by supplier regions (Figure 7.12(b)). In the line plot, each solid curve represents the percentage of total cement distribution directed to Europe, Africa, Asia, and North America, totalling 100 per cent when capacity is fully utilised; the dotted lines trace the evolution of carbon prices under the various APS policy mechanisms. Initially, Europe's share starts below the STEPS scenario baseline, reflecting APS's higher global carbon costs, which reduce the cost gap between regions and, therefore, make distributing to other regions more profitable. Asia's distribution share increases in the early years, as transporting cement from Asian facilities remains attractive when the free allowances phase out. From 2028 to 2029, a small but noticeable uptick in Asian-to-Europe shipments appears – driven by investment in Asian carbon capture capacity. Fluctuations in the regional distribution occur around 2032, 2033, and 2034, and again in 2038; each of these shifts reflects global carbon price adjustments that prompt the distribution flow to be re-optimised to maximise total profit. Compared to the STEPS scenario, the APS scenario

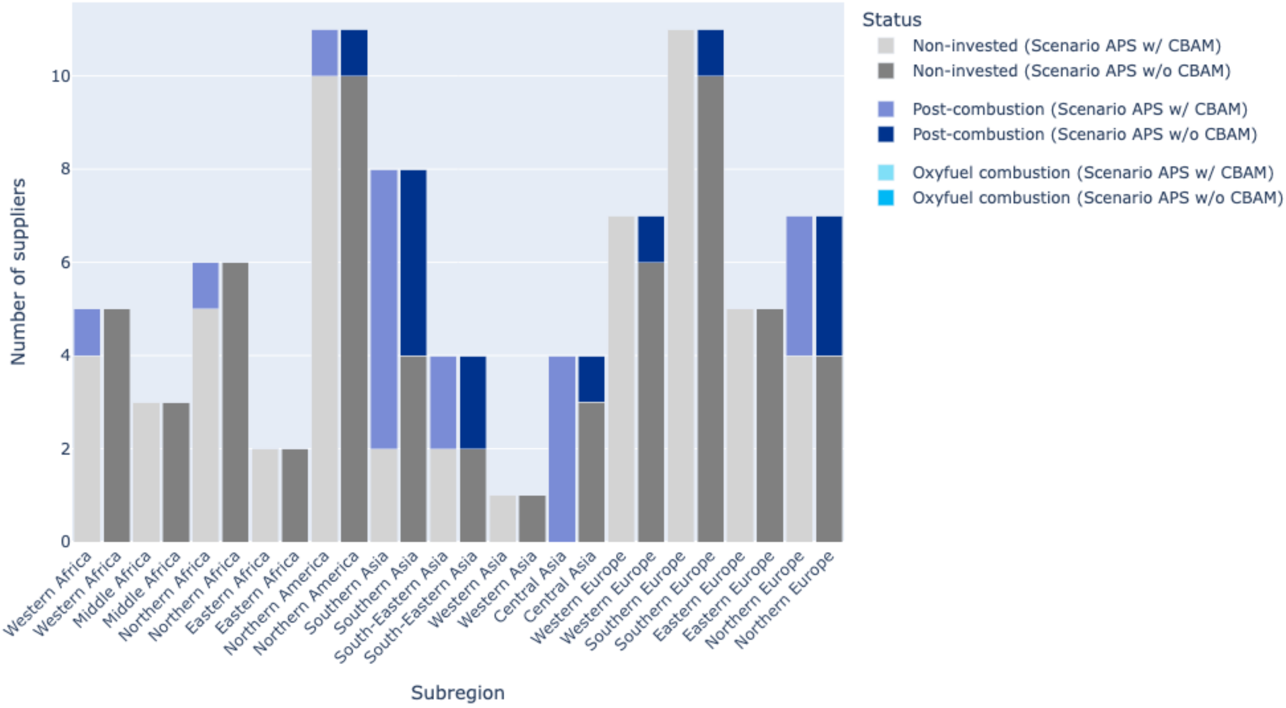
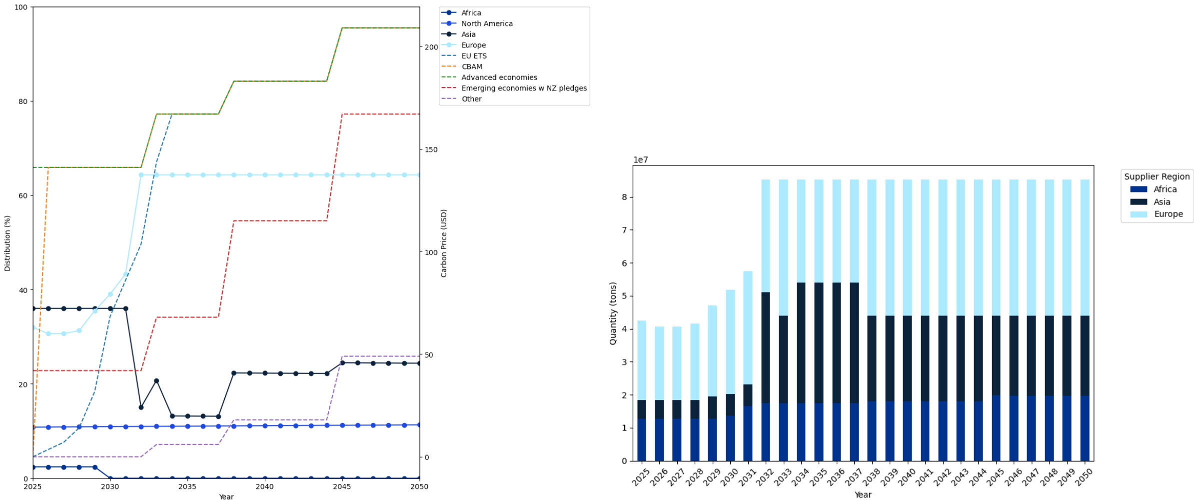


Figure 7.11: Comparison of investments made with or without the CBAM in the different subregions under the APS scenario.

without the CBAM makes Asian imports less financially attractive: Asia's market share in Europe remains lower overall, illustrating how strengthened carbon pricing elsewhere narrows the competitive gap between European and non-European producers.

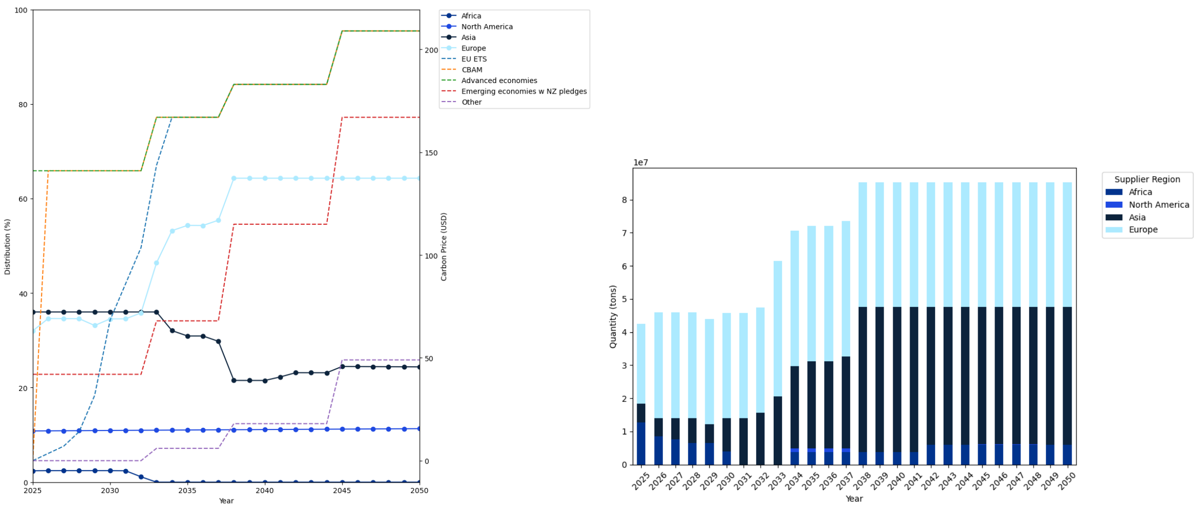


(a) Regional flow shares and carbon-price evolution under APS (without the CBAM).

(b) Europe's supply sources by region under APS (without the CBAM).

Figure 7.12: Distribution under APS without the CBAM. The line plot shows each region's share of the total distribution alongside the EU ETS price trajectory.

Figure 7.13 shows the corresponding distribution when the CBAM is applied. The maximum European market share is reached several years later than in the no-CBAM case, as the equivalent EU ETS levy on imports erodes the relative advantage of high-carbon foreign cement. Only two African plant retrofits exist under APS, so African exports to Europe remain relatively low compared to the case where the CBAM is not active. In the first half of the time horizon, Europe's domestic production remains unaffected. Conversely, in the second half, improved capture economics in Asia spur a renewed flow of Asian-produced cement back into Europe. These adjustments highlight how discrete carbon price jumps can trigger simultaneous reshuffles across all regions as firms seek to maximise profit under the CBAM framework (see also the regional breakdowns in section H.2).

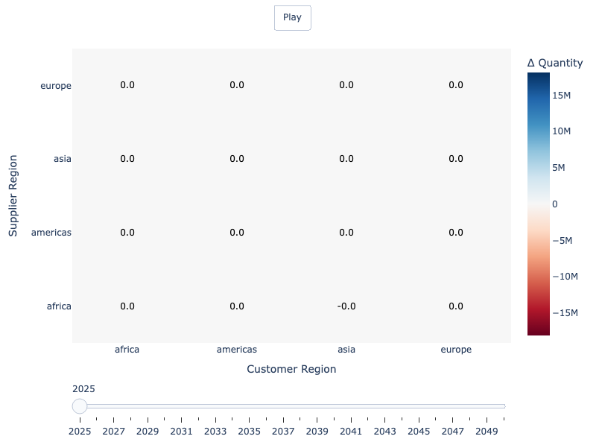


(a) Regional flow shares and carbon-price evolution under APS (with the CBAM).

(b) Europe's supply sources by region under APS (with the CBAM).

Figure 7.13: Distribution under APS with the CBAM. The line plot shows each region's share of total distribution alongside the EU ETS price trajectory.

Figure 7.14 presents six heatmaps – each for 2025, 2030, 2035, 2040, 2045, and 2050 – showing the difference in shipment volumes (CBAM active minus CBAM absent) between supplier and customer regions. In 2025 (Figure 7.14(a)), negligible differences appear, as the CBAM only comes into effect later. By 2030 (Figure 7.14(b)), Asian exports to Europe will increase slightly under the CBAM, driven by the expiration of free allowances elsewhere, while Europe boosts intra-regional shipments and Africa shifts volumes away from Europe toward the other regions. In 2035 (Figure 7.14(c)), the CBAM's levy begins to suppress Asian-to-Europe flows, rerouting those volumes back into Asia. After 2037, as carbon price differentials narrow, the non-CBAM Asian cement again favours inter-regional distribution, a trend that stabilizes through 2050. Throughout, Africa consistently reduces exports to Europe in favour of intra-regional and Asian markets.



(a) Snapshot year 2025.

(b) Snapshot year 2030.

(c) Snapshot year 2035.

(d) Snapshot year 2040.

(e) Snapshot year 2045.

(f) Snapshot year 2050.

Figure 7.14: Heatmaps of shipment-volume differences under APS (CBAM minus no CBAM) by supplier (rows) and customer (columns) at five-year intervals. Blue values indicate increased shipments under the CBAM; red indicates reductions; white indicates negligible change.

Under the APS scenario's elevated carbon pricing trajectory, ten core carbon capture and retrofit projects become economically viable, irrespective of the CBAM, with concentrations primarily in Asia, two in

Europe, and one in Canada. In the absence of the CBAM, three additional investments emerge in North America and Europe, reflecting APS's high domestic EU ETS prices, which narrow the cost gap between domestic and foreign production. Introducing the CBAM instead redirects these marginal projects to Southern and Central Asia, where lower production and transport costs prevail even after accounting for the import levy.

These investment patterns directly shape trade flows. Without the CBAM, Europe's market share rebounds swiftly as free allowance phase-outs boost domestic and nearby regional distribution, while Asian and African imports remain suppressed compared to the STEPS scenario. With the CBAM active, Europe's recovery is delayed: only one African retrofit limits African exports, and the additional Asian capture sites facilitate a renewed inflow of lower-cost foreign cement despite the levy.

Taken together, the APS results demonstrate that stringent carbon pricing alone can drive retrofit investments and support European distribution but that a CBAM import charge critically influences where marginal projects are located and, thus, which regions supply Europe over time.

7.4.2 Scenario NZE

Under the NZE scenario, which assumes that all major economies reach net-zero emissions by 2050 and that carbon pricing escalates rapidly to reflect this ambition, baseline investment and distribution patterns are first established before any CBAM enforcement takes effect. By comparing outcomes without the CBAM against those with the CBAM applied from 2026 onward, this section examines how CBAM affects both the geographic allocation of carbon capture investments and the flow of cement volumes into Europe under a near-zero-emissions policy environment. First, carbon capture investment decisions under NZE are examined[8]. Next, distribution decisions are analysed with a particular focus on Europe's market share, illustrating how the CBAM reshapes sourcing from Africa, Asia and domestic producers when carbon prices rise sharply across all regions. Finally, a series of heat maps, updated at five-year intervals, details the magnitude and direction of trade-flow adjustments induced by the CBAM under the NZE trajectory. Additional figures and details of the results can be found in section H.3.

Investment Decisions NZE

Under the NZE scenario's stringent decarbonisation pathway, the economics of retrofits diverge sharply from those in the STEPS and APS scenarios. Figure 7.15 illustrates the geographic distribution of all new carbon capture investments both with and without the CBAM. In the absence of the CBAM, a substantial proportion of retrofit projects are located within Europe, driven by the region's elevated domestic carbon price trajectory. The introduction of the CBAM, however, shifts the marginal projects to lower-cost regions outside Europe. This outcome suggests a potentially unintended consequence: by altering the relative economics of carbon capture investments, the CBAM may incentivise decarbonisation outside the EU rather than within it. A similar pattern emerged under the APS scenario, as discussed in section 7.4.1.

A subregional breakdown in Figure 7.16 makes this contrast explicit. Without CBAM, two additional retrofits appear in Western Europe, supplementing the core European portfolio. In contrast, activating CBAM shifts those marginal projects to Central Asia, Northern Africa, and Southern Asia, where lower per-ton costs outweigh Europe's import equivalent EU ETS levy.

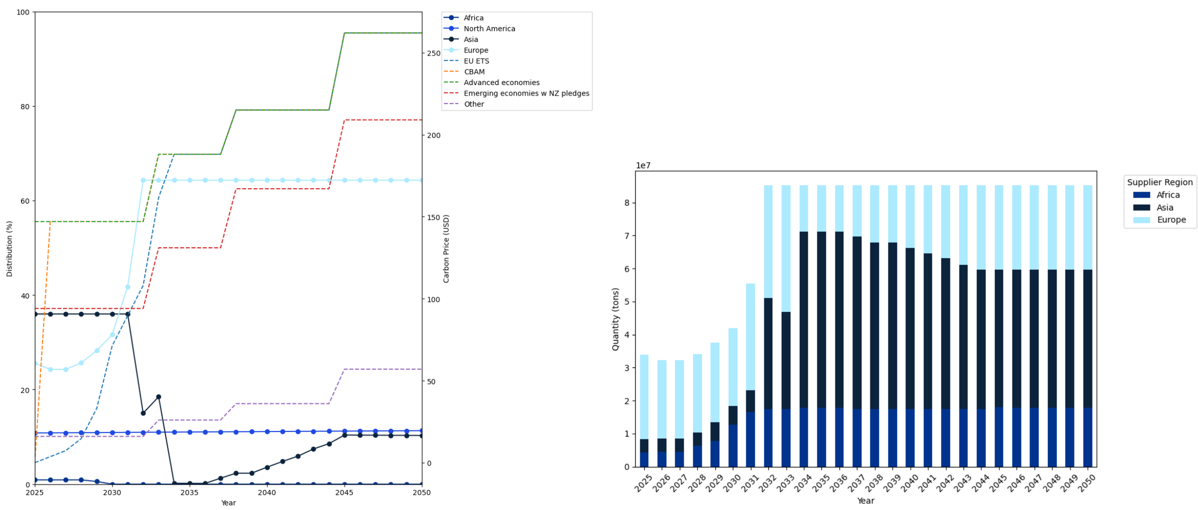
Distribution Decisions NZE

Figure 7.17 presents the NZE scenario distribution outcomes without the CBAM, combining a line plot of regional flow shares and carbon price trajectories (Figure 7.17(a)) with a stacked bar breakdown of Europe's supply sources (Figure 7.17(b)).

[8] Heidelberg Materials' existing Norwegian retrofit (Porsgrunn) is excluded from "new" counts but is depicted in the figures for completeness.

Figure 7.15: Geographic locations of the investments made under the NZE scenario.

Figure 7.17(a) illustrates that Europe's share of total cement distribution begins at levels below those observed under the STEPS scenario, a consequence of NZE's more stringent domestic carbon pricing, which narrows the cost differential. As free allowances phase out, Europe's share increases gradually toward its maximum, initially propelled by rapid expansion in African-sourced cement and modest gains from Asian suppliers. During the period of steepest allowance reductions, Asian-produced cement enters the European market in larger increments, eroding a substantial portion of domestic market share. From 2036 onward, however, European production regains ground – albeit slowly – reflecting the impact of newly commissioned carbon capture investments on European soil (see Table H).



(a) Regional flow shares and carbon-price evolution under NZE (no CBAM).

(b) Europe's supply sources by region under NZE (no CBAM).

Figure 7.17: Distribution under NZE without the CBAM. The line plot shows each region's share of the total distribution alongside the EU ETS price trajectory.

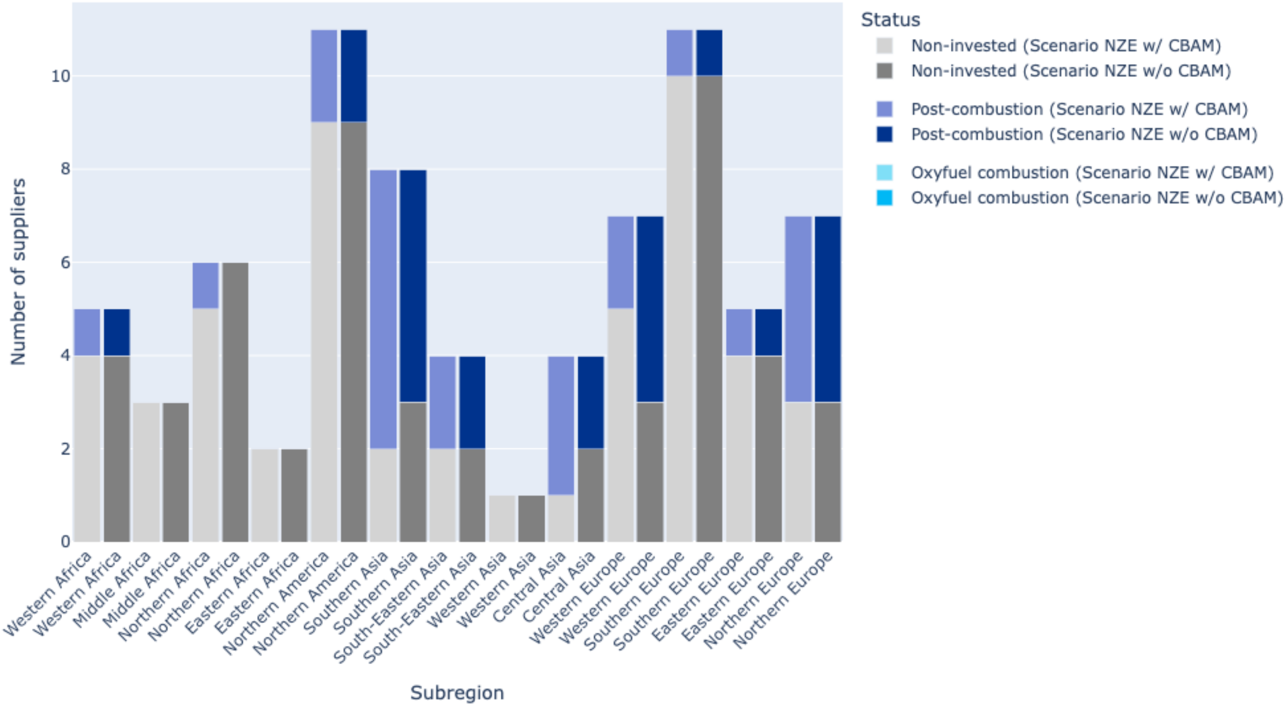
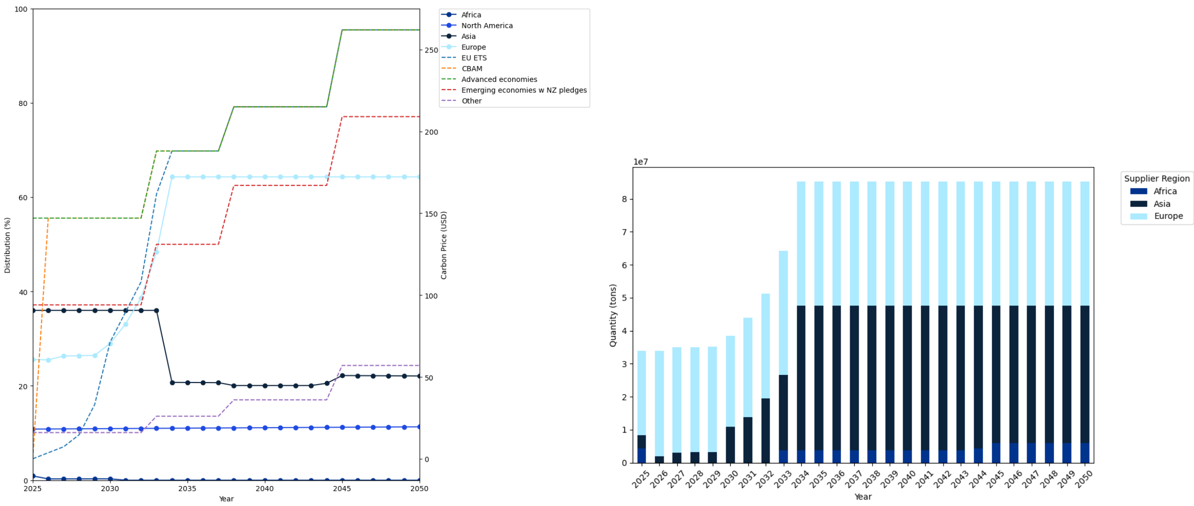


Figure 7.16: Comparison of investments made with or without the CBAM in the different subregions under the NZE scenario.

Figure 7.18 illustrates the NZE scenario under the CBAM. Europe's market-share trajectory closely parallels the no-CBAM case but attains its peak at a later date (Figure 7.18(a)), indicating that the import levy temporarily dampens the rebound in domestic supply. Upon the CBAM implementation, contributions from Asian and African suppliers declined marginally. During the steepest phase-out of free allowances, Asian-produced cement imports into Europe accelerate markedly, although they never regain the share held by domestic producers. African-sourced cement remains uncompetitive in the initial years; only as free allowances approach full elimination does its distribution to Europe begin to recover.

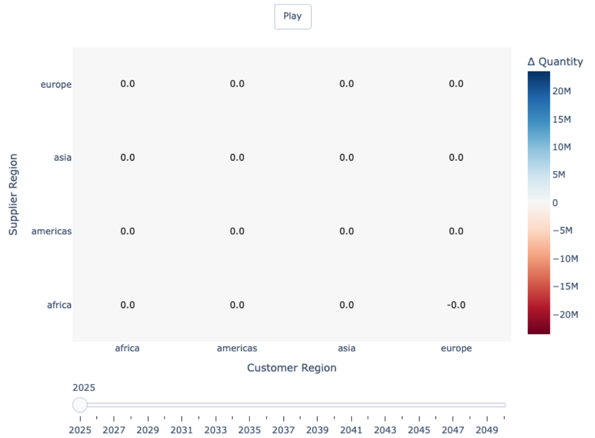


(a) Regional flow shares and carbon-price evolution under NZE (with the CBAM).

(b) Europe's supply sources by region under NZE (with the CBAM).

Figure 7.18: Distribution under NZE with the CBAM. The line plot shows each region's share of the total distribution alongside the EU ETS price trajectory.

Figure 7.19 shows six heatmaps (2025–2050) of shipment-volume differences (CBAM minus no-CBAM) by supplier and customer region. In 2030 (Figure 7.19(b)), modest reductions appear for European, Asian, and African exports to Europe, with those volumes rerouted inter-regionally – an early signal that the CBAM begins to curb carbon-intensive imports and shifts trade toward closer or lower carbon markets. By 2035 (Figure 7.19(c)), Europe is expected to increase self-supply and potentially even export small volumes to Asia and North America, reflecting both the dampening of inbound flows and the improved competitive position. Meanwhile, Asia and Africa continue to redirect exports toward non-European markets, illustrating the role of the CBAM in reshaping global trade patterns. Beyond 2040, the same trends persist but at lower magnitudes.



(a) Snapshot year 2025.

(b) Snapshot year 2030.

(c) Snapshot year 2035.

(d) Snapshot year 2040.

(e) Snapshot year 2045.

(f) Snapshot year 2050.

Figure 7.19: Heatmaps of shipment-volume differences under NZE (CBAM minus no CBAM) by supplier (rows) and customer (columns), at five-year intervals. Blue values indicate increased shipments under CBAM; red indicates reductions; white indicates negligible change.

Under the NZE pathway's stringent decarbonisation framework, European retrofits are initiated even without the CBAM, driving a concentration of core investments on the continent. Introducing the CBAM shifts projects from Western Europe to lower-cost regions (Central Asia, Northern Africa, and Southern Asia), demonstrating how an import equivalent levy rebalances the investment calculus despite aggressive global carbon prices.

These investment shifts reverberate through trade patterns. Without the CBAM, Europe initially surrenders market share to Asian and African exporters but then recovers rapidly as free allowance phase-outs raise carbon costs abroad. Applying the CBAM delays Europe's rebound and reroutes early volumes into inter-regional flows, as indicated by the 2030 heatmap snapshots. By 2035, enhanced European capture capacity not only restores home market supply but also generates modest exports to Asia and North America. After 2040, with capture investments and allowance schedules stabilised, the CBAM's incremental impact on shipment volumes diminishes.

Together, the NZE scenario results underscore that while NZE's high domestic carbon price drives European self-sufficiency, the CBAM remains pivotal in steering marginal investments and reshaping global cement flows over time.

Across the three carbon pricing pathways – STEPS, APS, and NZE – the CBAM consistently emerges as a pivotal mechanism in shaping investment and trade flow outcomes for Heidelberg Materials. Under STEPS, retrofit economics remain economically unviable in Europe, absent the CBAM, leading to carbon capture projects clustering in low-cost Asian sites only once the border levy is applied. In the APS and NZE scenarios, more stringent domestic carbon prices render European retrofits economically viable even without the CBAM; nevertheless, the introduction of the CBAM results in reorienting investments toward Southern and Central Asia (APS) or Central Asia, Northern Africa, and Southern Asia (NZE). This redirection of marginal projects highlights a potentially unintended consequence: the CBAM may incentivise decarbonisation activities outside the EU rather than within it, thereby shifting the focus of new decarbonisation investments away from European facilities.

Across the STEPS and NZE pathways, the CBAM reinforces Europe's competitiveness. Under the STEPS scenario, domestic retrofits remain uneconomic. When the CBAM is applied, investments in carbon capture technologies become economically viable within low-cost regions. At this point, low-cost foreign plants must either decarbonise or redirect volumes, allowing European production to regain market share.

In summary, while robust carbon pricing frameworks can independently stimulate retrofit activity and enhance European self-sufficiency, the CBAM plays a critical role in determining the geographic allocation of final investments across all scenarios and in reshaping global cement trade flows over time, particularly under the STEPS and NZE pathways. These insights serve as the foundation for the industry and policy-oriented conclusions presented in the following chapter.

Chapter 8

Conclusion

This chapter serves to answer the primary research question:

'How does the Carbon Border Adjustment Mechanism impact the optimisation of strategic investment in carbon capture production technologies and cement distribution within global supply chains?'

This research question was addressed through extensive data gathering, forecasting, the development of a mathematical optimisation model, and the execution of sensitivity and scenario analyses. With the use of these methodologies, this thesis provides a decision-support framework that can be used for optimising investment decisions under varying carbon pricing policies applicable to industry purposes. It also provides insights into the effects of carbon pricing policies on the industry's supply chain.

This conclusion synthesises how the CBAM influences both strategic investments in carbon capture and global cement trade flows, based on a case study of Heidelberg Materials under three carbon pricing pathways (STEPS, APS, and NZE). It begins by addressing the secondary research questions, highlighting the key findings, and deriving implications for both industry and policy. The chapter concludes by outlining the scientific contribution of this study.

8.1 Secondary Questions

Each secondary question, which leads to answering the primary research question, will be discussed in this section.

SQ1: 'What are the primary cost and emissions drivers affecting decisions on cement flow and green technology investments?'

The analysis reveals that four categories of drivers fundamentally shape decisions on cement distribution and investments in carbon capture technologies: regional production costs, transportation costs, investment costs, and carbon-related costs – including carbon pricing mechanisms and the costs associated with transporting and storing captured carbon.

First, regional production costs vary significantly across the globe. Accurately representing these disparities in the model is crucial for realistically capturing the competitiveness of production sites, as lower-cost plants can offer more attractive options for investment and exports.

Second, transportation costs play an equally decisive role. Even when production costs are low in a particular region, the profitability of serving distant, high-value markets depends on whether freight costs preserve sufficient margins. The interdependence between production and transportation costs is therefore central to determining optimal trade routes and supplier–customer allocations. Additionally, transportation cost dynamics can vary substantially even for origin-destination pairs with identical distances or for the same pair, depending on the shipment direction. Accurately modelling these nuances is essential to capture a realistic representation of the cement supply chain and ensure reliable optimisation results.

Third, carbon pricing mechanisms are pivotal drivers. These mechanisms increase operating costs at the high-emission plants, shifting incentives toward cleaner production technologies. They also affect trade patterns by imposing additional costs on the embedded emissions of imported cement, changing the relative competitiveness of suppliers in different jurisdictions.

Additionally, decisions about retrofitting plants with carbon capture technologies hinge on investment-specific factors such as capital expenditures, expected capture rates, technology availability timelines, and potential downtime during installation. The feasibility of retrofits also depends on logistical considerations, such as the availability and cost of transporting and storing captured carbon, which must be included in the model to reflect realistic implementation costs.

By integrating these drivers – regional production and transportation costs, carbon pricing impacts, and technology-specific investment parameters – this thesis develops a robust decision-support framework. This framework optimises both cement distribution and strategic investments in carbon capture technologies, providing actionable insights for industry stakeholders and policymakers striving for effective decarbonisation.

SQ2: 'What data and parameters are required to develop a mathematical model that integrates the CBAM costs, cement flow, and technology investments?'

Developing an integrated optimisation model requires comprehensive data describing both supply and demand dynamics. On the supply side, the model needs detailed information for each cement plant, including its geographic location, ownership, and production capacity, to enforce supply limits and calculate transport distances accurately. For the demand side, historical national cement consumption must be reconstructed by combining domestic output and bilateral trade data. This reconstructed demand is then projected across the three largest cities, based on population, to create a more geographically realistic scenario.

Specifying emissions factors and carbon price trajectories is also essential. Baseline direct and indirect carbon intensities per ton of cement provide the foundation for emissions calculations, while expected capture rates post-retrofit determine residual emissions levels. These emissions data are paired with region-specific carbon price pathways, incorporating the CBAM, which begins phasing in from 2026 and progressively replaces free allowances under the EU ETS.

Logistics inputs are equally critical for modelling realistic distribution decisions. To capture the economic implications of global bulk cement transport, a cost matrix was developed based on per-ton freight rates between subregions and adjusted for actual plant-to-market distances. The matrix is directionally dependent on origin and destination, ensuring a realistic representation of real-world transportation dynamics.

Finally, technology investment parameters define the feasibility and attractiveness of decarbonisation options. For each carbon capture technology – post-combustion and oxy-fuel combustion – the model requires estimates of capital expenditures, regionally adjusted production costs, expected capture efficiencies, retrofit feasibility, and downtime, as well as the costs associated with transporting and storing captured carbon via pipelines, ships, or trucks. Together, these datasets enable the model to optimise both cement routing and carbon capture investments in response to evolving carbon pricing regimes and market conditions.

SQ3: 'How can a mathematical optimisation model be developed to integrate cement flow and investment decisions in carbon capture technologies while accounting for the CBAM-related costs?'

To address this research question, a Mixed-Integer Linear Programming (MILP) model was developed to simultaneously optimise investment decisions in carbon capture technologies and the distribution of cement across global markets. The model is structured around a Transportation Problem framework, modelling both distribution and strategic investment decisions. Instead of cost-minimisation formulations, the objective function is designed to maximise profit by subtracting all incurred costs – including production, transport, carbon, CBAM-related levies, and investment expenses – from the expected revenues generated per ton of cement sold in a specific region.

The model uses two key decision variables: the continuous variable x_{ijte}, representing the amount of cement allocated from production facility i to customer j in year t, conditional on investment status ϵ; and the binary variable y_{iet}, which indicates whether a specific carbon capture technology has been installed at plant i in year t. By linking these decisions with regional production costs, transport costs, carbon prices, and the CBAM adjustments, the model integrates investment timing and location choices with optimal cement flows, providing a coherent decision-support tool for assessing supply chain strategies under dynamic carbon pricing regimes.

SQ4: 'How do different carbon pricing scenarios influence the impact of the CBAM on these decisions?'

Under the STEPS scenario, which assumes the continuation of current and announced policies, domestic carbon prices in Europe remain relatively low until free allowances are phased out. In this setting, European carbon capture retrofits are not economically viable without the CBAM. Only with the introduction of the CBAM in 2026 do capture investments in low-cost regions such as South, Southeast, and Central Asia become profitable. The CBAM also helps preserve European market share by imposing an ETS-equivalent surcharge on imports, discouraging foreign producers from undercutting domestic suppliers and shifting Asian-produced cement back to intra-regional markets.

In the APS scenario, which incorporates moderately higher carbon prices aligned with announced net-zero pledges, ten core retrofits – seven in Asia, two in Europe, and one in North America – are already profitable even without the CBAM. However, activating the CBAM realigns marginal investment decisions, redirecting them away from higher-cost European sites toward more cost-effective plants in Southern and Central Asia. This shift in profitability is driven by the free allowances phase-out, which significantly increases the carbon costs for domestic production. As a result, the estimated revenue from avoided emissions rises, further widening the profit gap in favour of external regions such as Africa and Asia, where production costs remain relatively stable. On the distribution side, while the CBAM reduces the competitiveness of imports, it has a limited impact on the trade flows of the case study in this scenario; distribution patterns remain largely stable, as the higher carbon prices alone are sufficient to drive investment and shape market dynamics.

Under the NZE scenario, characterised by a steep increase in carbon prices necessary for achieving net-zero emissions by mid-century, European retrofits become economically viable even in the absence of the CBAM. Yet when the CBAM is introduced, the model again shifts marginal investment projects toward regions like Central Asia, Northern Africa, and Southern Asia, where the gap remains profitable despite the added import charges. The profitability shift is primarily triggered by the phase-out of free allowances, which raises the effective carbon cost for European producers. This increase enhances the estimated revenue benefit from emissions abatement, thereby expanding the profitability advantage of producers in regions like Africa and Asia, where production costs remain largely unchanged. Trade flows under the NZE scenario initially show Europe losing market share to foreign suppliers due to high domestic carbon costs, but the application of the CBAM ultimately redistributes cement flows, restoring a larger share of European-produced cement to European markets.

In summary, more stringent carbon pricing enhances the standalone viability of domestic carbon capture investments. While the CBAM is a key factor in determining the location of marginal retrofit projects across all scenarios, its effectiveness in reshaping global cement trade flows – by ensuring that European-produced cement remains competitive within Europe – is primarily observed in the STEPS and NZE scenarios.

SQ5: 'What insights and recommendations can be gained from applying the model to a case study?'

The Heidelberg Materials case study anchors the model in a representation of real-world operations, illustrating how plant-specific factors significantly influence the viability of carbon capture investments. Under the STEPS pathway, for instance, only the lowest-cost plants clear the economic threshold once the CBAM is introduced, while higher-cost facilities remain uncompetitive. This, in combination with the results from the sensitivity analyses, indicates that the solution changes most significantly with increases and decreases in production costs, demonstrating that production cost differentials significantly influence the investment decision. Crucially, the sensitivity analysis reveals that relatively minor adjustments in regional production costs can swing entire retrofit portfolios from uneconomic to attractive, underscoring the importance of precise local cost data and suggesting that targeted subsidies or incentives in those regions could tip the balance toward meaningful decarbonisation investments. The case study also suggests that the other cost components in the model largely offset transportation costs. Decreasing or increasing these costs has no significant effect on the model's output.

Moreover, the case study reveals that other cost components, including transportation and investment costs, generally offset one another in the model. Adjusting these elements has minimal influence on overall investment decisions, reinforcing the centrality of production cost differentials as the dominant driver. These insights offer valuable guidance for policymakers and industry stakeholders, highlighting where policy interventions or strategic cost reductions could have the most significant impact in accelerating emissions reductions in the cement sector.

In addressing the main research question – *How does the Carbon Border Adjustment Mechanism impact the optimisation of strategic investment in carbon capture production technologies and cement distribution within global supply chains?* – this thesis demonstrates that the CBAM fundamentally reshapes both the geographical allocation of decarbonisation investments and the patterns of international cement trade. By embedding the full cost of carbon into import prices, the CBAM alters relative competitiveness, preserving domestic market share for lower-carbon producers while penalising high-emission imports.

The integrated MILP framework developed in this study reveals that, under the STEPS scenario, investments remain uneconomical within Europe without the CBAM; the border levy becomes the decisive factor in encouraging retrofits in low-cost regions outside the EU. Under APS, higher carbon prices alone incentivise significant investments in Asia and some in Europe, but the CBAM still shifts marginal projects toward lower-cost overseas plants. In the NZE scenario, steep domestic carbon prices make European retrofits economically viable even without the CBAM. However, the regulation continues to fine-tune the geographic allocation of investments outside Europe and reinforces Europe's competitiveness in trade flows. These results confirm that the CBAM's influence varies with the level of global carbon pricing: it is pivotal under the STEPS and NZE carbon price trajectories but plays a more secondary role under the APS pathway.

Operationally, the CBAM's introduction reshapes trade flows by eroding the price advantage of imports from traditionally low-cost regions unless those suppliers invest in carbon capture. This dynamic restores or preserves European suppliers' market share under both conservative and aggressive pricing scenarios. Meanwhile, the sensitivity analysis highlights that among the cost parameters, production cost differentials are the dominant driver of investment decisions: modest changes in these costs can swing entire retrofit portfolios from economically unviable to attractive. In contrast, variations in other factors have a limited impact on optimal investment outcomes.

While the MILP approach successfully integrates investment decisions and trade routing under dynamic carbon pricing scenarios, it relies on linear cost assumptions and static production capacities. These necessary simplifications enhance computational tractability but may overlook potential nonlinear effects like economies of scale or capacity expansions, which could further influence optimal strategies.

Beyond these insights, the Heidelberg Materials case study validates the model's practical relevance. It shows that plant-specific production cost factors drive investment decisions the most and that modest shifts in production costs can tip portfolios from unviable to attractive. Collectively, the results provide a robust decision-support framework for industry stakeholders to plan for capturing investments and distribution strategies under evolving policy regimes, as well as for policymakers to calibrate the CBAM design. In doing so, this research offers a clear, evidence-based path toward aligning global cement trade with stringent climate objectives.

8.2 Policy Insights

The findings from this research provide valuable policy insights into how regulatory frameworks, particularly the CBAM, influence investment and operational strategies within the cement industry. By examining the implications of carbon border adjustments alongside detailed sensitivity analyses, this section highlights practical considerations for policymakers and cement producers alike, guiding strategic decisions to effectively balance economic competitiveness with climate policy objectives.

8.2.1 Insights for Regulators

The findings of this research highlight that the CBAM fundamentally alters investment patterns in carbon capture technologies, often redirecting projects to lower-cost regions outside Europe when the regulation is active. This suggests that while the CBAM effectively internalises the cost of carbon for imports, it alone is not sufficient to drive large-scale retrofits within the EU's borders. Policymakers should therefore consider complementing the CBAM with targeted support mechanisms – such as direct subsidies, tax credits, or other incentives – to help European cement plants that are just shy of profitability undertake carbon capture retrofits. By strategically supporting these plants, the EU can better align the CBAM's protective function with its climate objectives, ensuring that decarbonisation investments stay within Europe rather than shifting abroad.

Furthermore, the research underscores the critical importance of robust, standardised emissions and cost data. Mandating transparent, plant-level reporting frameworks would improve the accuracy of industry-wide models and enhance policymakers' ability to calibrate instruments like the CBAM effectively. Such transparency would also provide clarity to market participants, reducing investment uncertainty.

In addition, policymakers should work towards international cooperation with key trading partners to harmonise carbon pricing efforts. Aligning carbon pricing standards and sharing best practices would reduce the risk of trade disputes, limit unintended carbon leakage beyond EU borders, and strengthen global climate action.

8.2.2 Insights for Cement Companies

For cement producers, these findings underscore the necessity of proactively monitoring carbon pricing trajectories and understanding the CBAM's evolving design. Firms that integrate carbon cost considerations into their distribution strategies will be better equipped to minimise exposure to rising import levies and maintain market competitiveness. Optimising distribution networks – by reassessing routes and destination markets – will become increasingly important as carbon costs reshape regional competitiveness.

Moreover, the sensitivity analysis reveals that shifts in production costs can have a significant impact on the attractiveness of investment. Cement companies should therefore prioritise developing accurate, plant-level data systems to monitor production costs and emissions intensities. Enhanced internal data not only supports better investment decisions but also prepares firms for potential future regulatory requirements mandating cost and emissions transparency. Together, these measures can help companies anticipate market changes, capitalise on policy incentives, and position themselves effectively in a decarbonising global cement market.

8.3 Scientific Contribution

This research advances the scientific understanding of decarbonisation strategies within the cement industry by developing and applying an integrated modelling framework that unites strategic investment and distribution decisions under dynamic carbon pricing regimes. Specifically, the study contributes a MILP formulation that explicitly incorporates technology-specific retrofit investments, regionally disaggregated production and transport costs, carbon pricing mechanisms, and the effects of the CBAM.

Methodologically, the thesis contributes a validated end-to-end modelling pipeline that begins with extensive data collection and preprocessing, proceeds through long-term demand forecasting, and culminates in a comprehensive optimisation model. The framework's ability to simultaneously evaluate binary investment choices and continuous cement flows represents a significant improvement over existing approaches, which typically isolate these decision layers or overlook the interplay between carbon pricing and supply chain dynamics. The incorporation of sensitivity and scenario analyses further strengthens the model by systematically assessing its robustness to uncertainties and exploring the implications of alternative future policy pathways.

Empirically, this research provides original insights into how carbon pricing trajectories and the CBAM implementation jointly determine the economic feasibility and optimal location of carbon capture investments in the cement industry. By modelling plant-level costs and emissions intensities across diverse global regions, the study reveals how production cost differentials can shift retrofit portfolios, underscoring the critical importance of local economic conditions in shaping decarbonisation strategies.

The study's findings contribute to the broader scientific literature by demonstrating how integrated optimisation methods can inform both corporate investment planning and climate policy insights. The model serves as a decision-support tool that can be used within the cement industry and adapted to other similar energy-intensive industries facing comparable challenges, offering a scalable approach for evaluating long-term strategies under complex, evolving regulatory frameworks. By combining detailed empirical data with advanced optimisation techniques, this thesis lays the groundwork for future research exploring the interactions between carbon policies, global trade flows, and investment dynamics in industrial decarbonisation.

Chapter 9

Discussion and Future Research

This chapter synthesises the key findings of the decision-support framework for strategic investment in carbon capture and cement distribution under evolving carbon pricing mechanisms. The "Discussion" first interprets the model results, highlights critical insights on investment decisions and carbon leakage under different scenarios, and identifies areas where modelling choices and data assumptions may affect conclusions. By critically examining omissions, the discussion both validates the robustness of core outcomes and acknowledges the limits of the current approach.

Building on these reflections, the "Future Research" section proposes four targeted extensions to strengthen and expand the decision-support tool. The first explores the optimal design and allocation of government subsidies to bridge investment gaps and accelerate the deployment of carbon capture within Europe. The second broadens the model's scope to assess complementary decarbonisation levers and their interactions with capture investments. The third introduces the concept of carbon as a tradable commodity, modelling potential revenue streams from carbon sales markets and their impact on carbon capture investments. The fourth discusses the integration of LCA within the model.

9.1 Discussion

This study demonstrates that integrating investment decisions in carbon capture technologies with cement distribution under evolving carbon pricing policies provides a richer understanding of how instruments such as the CBAM reshape decarbonisation pathways. By coordinating capture retrofits with distribution choices, the MILP model shows that regional cost advantages can decisively shift investment locations, underscoring the need for holistic approaches to cement sector decarbonisation. This unified perspective addresses a gap in existing studies, which typically treat investment and logistics decisions separately and do not consider evolving carbon pricing schemes.

However, several assumptions inherent in the modelling framework limit its ability to reflect real-world complexities fully. Most notably, the exclusive use of linear cost functions implies constant marginal costs for production, transportation, and retrofit investments, thereby excluding nonlinear effects such as economies of scale that could affect investment timing or distribution choices. While this linearity ensures computational efficiency, it simplifies decision dynamics and may underestimate opportunities for strategic portfolio optimisation. Future model extensions, such as those employing piecewise-linear approaches, could capture these dynamics more realistically, albeit at the cost of increased computational demands and more accurate data.

The omission of maritime transport emissions from the analysis also represents a notable limitation, particularly given that the EU ETS has begun regulating shipping emissions. Including these emissions would likely influence the optimal trade flows, potentially further amplifying the competitive advantage of European or near-market producers. This integration requires detailed modal-choice modelling and route-specific data, but represents an important avenue for future research better to reflect the actual carbon footprint of global cement trade.

Additionally, the current model assumes uniform retrofit feasibility across all plants and technologies. In practice, site-specific factors such as layout constraints and local infrastructure can materially affect retrofit costs and feasibility. While this study relies on literature-derived average data to ensure generalisability, incorporating plant-level cost and emissions data through industry collaboration would enhance the precision of investment forecasts and strengthen the model's real-world applicability.

The use of a single, averaged emission intensity likewise masks product-specific variation. For example, CEM I Portland cement – composed of over 95% clinker exhibits substantially higher carbon intensity than blended products such as CEM II or CEM III (CEMEX, 2020; van Gijlswijk et al., 2015). Disaggregating the model by cement type would heighten precision and better capture real-world substitution effects under carbon pricing. Additionally, reliance on default emission factors and production costs overlook plant-level performance differences; incorporating measured site data would improve the realism of carbon-cost estimates and strengthen the reliability of the model's output.

Moreover, the model exclusively examines carbon capture retrofits, without considering other decarbonisation strategies such as alternative fuels or clinker substitution. These options could offer complementary or lower-cost pathways to emissions reductions. Future research should integrate these measures to capture the full range of technology synergies and trade-offs available to cement producers.

Another omission is the potential for selling captured carbon as a commodity. Emerging commercial applications, such as synthetic fuels or enhanced greenhouse agriculture, could transform captured carbon from a pure liability into a revenue stream, improving the financial attractiveness of carbon capture projects (Bipartisan Policy Center, 2021; Doyle, 2018). Including these revenue opportunities in the optimisation framework would allow for a more comprehensive evaluation of the economic case for capture investments.

Finally, this study's findings carry implications beyond Europe. Other jurisdictions may adopt similar border carbon adjustments or alternative trade measures in response to the CBAM, potentially shifting global trade patterns or triggering regulatory convergence. Incorporating international policy responses into the modelling framework would add geopolitical realism and provide valuable insights for both global policymakers and industry decision-makers.

Together, these reflections highlight both the strengths of the developed framework and the limitations that future research should address. By extending the model's scope and integrating more granular data, decision-support tools for the cement sector can become more accurate, comprehensive, and aligned with the evolving realities of global climate policy and industrial decarbonisation.

9.2 Future Research

In recognition of the framework's limitations, this section outlines four extensions to enhance the decision-support tool for decarbonising the cement sector. First, the role of government subsidies is examined to determine how public funding can best bridge investment gaps and accelerate the deployment of capture. Second, the scope is broadened beyond carbon capture to include alternative fuels and clinker substitution. Third, emerging commercial markets for carbon as a tradable commodity are introduced to capture potential revenue streams and inform investment and transportation decisions. Lastly, the integration of LCA into the MILP framework.

9.2.1 Impact of Government Subsidies on Decarbonisation

The current MILP framework omits government subsidies due to limited data availability and high uncertainty around getting funding (A European Strategy for Carbon Capture and Storage, 2022). Nevertheless, both the EU ETS auction revenues and the CBAM proceeds represent a significant source of public funding that could accelerate the deployment of carbon capture within the EU. Understanding how to channel these funds most effectively is critical to ensuring that decarbonisation occurs on European soil. Future work could explore how revenues from the EU ETS and CBAM might be channelled into targeted subsidy schemes to accelerate carbon capture deployment in the EU27 cement sector. Three key questions merit investigation: which financial instrument – CAPEX grants, OPEX support or a hybrid design – yields the greatest uptake of retrofit investments; what minimum subsidy level is required to render representative carbon capture projects financially viable; and how a fixed public budget can be optimally allocated across candidate plants to maximise carbon abatement.

To address these questions, the developed MILP framework of this study could be augmented with subsidy decision variables and budget constraints. Scenario analysis could then compare scheme variants – such as CAPEX-only, OPEX-only, and mixed designs – across multiple overall budget envelopes. Inputs would include the CBAM proceeds, plant-level cost and emissions data, and eligibility criteria derived from EU policy. Such an exercise would provide policymakers with quantitative guidance on designing cost-effective subsidies. This can subsequently be used to optimise fund allocation, thereby helping to bridge the investment gap in Europe's efforts to decarbonise the cement industry.

9.2.2 Broader Decarbonisation Methods and Technologies

Future research could broaden the current MILP framework to explore integrated decarbonisation pathways that combine carbon capture with alternative fuels and clinker-substitution materials, thereby revealing synergistic portfolios that minimise carbon emissions and system costs. This effort would introduce decision variables for fuel choice (e.g. biomass, waste-derived fuels) and blend proportions (e.g. fly ash, slag) alongside capture sizing, incorporating availability and substitution constraints (Chatziaras et al., 2016; Khan et al., 2025; Kusuma et al., 2022; Park & Lee, 2024). Key analyses would quantify the techno-economic potential of non-capture levers at the source, assess how lowered clinker rates affect capture design and costs, and identify the least-cost mixes of measures under various carbon price and policy scenarios. Scenario and stochastic analyses could capture supply uncertainties for fuels and supplementary cementitious materials. The resulting decision-support tool would enable policymakers and industry stakeholders to evaluate "pathway mixes" – balanced portfolios of fuels, materials, and capture investments – that achieve emissions targets at minimum cost, thus guiding strategic planning for a deeply decarbonised cement sector.

9.2.3 Carbon as a Commodity: Modelling Carbon Sales Markets

Future work could augment the MILP framework by treating captured carbon not only as an emissions liability but also as a potential revenue-generating commodity, reflecting emerging utilisation pathways in synthetic fuels, chemicals and building materials (Bipartisan Policy Center, 2021). This extension would introduce dual destination nodes – transport and storage, with per-unit transport and sequestration costs, and carbon sales, with per-unit revenue – enabling allocation decisions for each plant and time period that balance geologic storage against marketable sales. Model parameters would draw on pilot-scale transactions and market forecasts to map evolving demand under low-, medium- and high-maturation scenarios, while sensitivity analyses would explore how price signals influence capture investment and distribution strategies. By quantifying potential sales revenues alongside disposal costs, this integrated approach would illuminate how market development could reshape the economics of carbon capture in cement production and inform strategic planning for investment and infrastructure deployment.

9.2.4 Integrating Life-Cycle Assessment

A promising extension of the current MILP is to embed environmental impacts directly into the decision-making framework alongside financial metrics. By defining per unit life cycle impact coefficients – e.g. l_{ie}^{eo} for end of life decommissioning – you can augment the existing objective or introduce a constraint capping total life cycle impact. This approach preserves the MILP's linearity and fast solve times while enabling a second objective (minimise total LCA impact) or a constraint limiting effects. It follows the SecMOD framework for combining MILP and LCA (Reinert et al., 2023).

In summary, this chapter has situated the framework's core findings within a broader analytical context and delineated clear avenues for extending the model's relevance. By integrating investment and logistics in a single optimisation, the thesis contributes to the scientific literature through a novel, unified approach that links carbon pricing, regional cost differentials, investment and operational decisions. Practically, it offers a decision-support tool that policymakers and industry stakeholders can use to evaluate both existing CBAM effects and help with their strategic investment decisions.

While certain simplifications warrant further refinement, the proposed future research directions – on government subsidy design, holistic decarbonisation pathways, and emerging carbon commodity markets – provide a roadmap for enhancing the model's realism. Ultimately, this work advances our understanding of how strategic investments can be guided under evolving carbon regulation regimes, and it lays the groundwork for more comprehensive, policy-relevant insights into the cement sector's decarbonisation.

Appendix A

Phase Out Free Allowances

The CBAM factor represents the proportion of free allowances still allocated under the EU ETS to covered sectors. These factors are used in the model to calculate carbon costs net of free allocation. The percentages are provided in Table A.1.

Year	Percentage
2025	100.0 %
2026	97,5 %
2027	95.0 %
2028	90.0 %
2029	77,5 %
2030	51,5 %
2031	39.0 %
2032	26,5 %
2033	14.0 %
2034	0.0 %

Table A.1: Annual CBAM factor values indicating the percentage of free emission allowances still granted under the EU ETS for CBAM-covered sectors from 2025 to 2034 (European Union, 2023).

A.1 Construction of the Emissions Cost Parameter

The parameter ψ_{iet} in the optimisation model represents the cost of carbon emissions incurred from producing one ton of cement at supplier location i using technology e in year t. This parameter plays a central role in capturing the emissions-related component of total production costs and is adjusted based on jurisdiction-specific carbon pricing policies.

To compute ψ_{iet}, the model uses the emissions intensity of each carbon capture technology, scaled by the carbon price applicable to the supplier's location and time period. Additionally, for supplier countries subject to the EU ETS, a phase-out factor is applied to account for the gradual reduction in free emissions allowances between 2026 and 2033.

The emission cost, ψ_{iet}, is calculated using the formula provided in Equation A.1. Here E_e corresponds to the emitted amount of emissions by production of one ton of cement using investment e, CP_{it} stands for the carbon price supplier i occurs in year t. This carbon price is gathered from one of the scenarios provided by IEA (2024), which can be found in section 4.2. Lastly, the term $(1 - F_{it})$ represents the potential reduction in price due to the free allowances rate of that year for the suppliers who are under the EU ETS jurisdiction (International Carbon Action Partnership, 2025).

$$\psi_{iet} = E_e C P_{it}(1 - F_{it}) \tag{A.1}$$

Appendix B

Inflation Adjustments and Currency Conversion

Historical prices were first adjusted for inflation to reflect their equivalent value in 2025, using the modified Laspeyres index formula given in Equation B.1 (U.S. Bureau of Labor Statistics, 2025a). For Euro values, adjustments were based on the Harmonised Index of Consumer Prices (HICP), as shown in Table B.1, while USD values were adjusted using the Consumer Price Index (CPI), as shown in Table B.2. The HICP for the euro was only available until 2024; therefore, the euro values of 2024 will be used as estimates for 2025. Subsequently, where required, all prices were converted to USD using an exchange rate of €1 = \$1.13, based on the European Central Bank's data from May 2025 (European Central Bank, 2025).

$$P_{j2025} = \frac{P_{jt}}{[\frac{IX_{jt}}{IX_{jt2025}}]} \tag{B.1}$$

Table B.3: Conversions made in the report (conversion rate €1 = \$1.13).

Original price	Year	Currency	Inflation index	Inflation index 2025	Inflated price	Exchanged price	Reference
126	2023	\$	304.702	318.851	132	132	(IEA, 2024)
21	2023	\$	304.702	318.851	22	22	(IEA, 2024)
24	2023	\$	304.702	318.851	25	25	(IEA, 2024)
28	2023	\$	304.702	318.851	29	29	(IEA, 2024)
39	2023	\$	304.702	318.851	41	41	(IEA, 2024)
43	2023	\$	304.702	318.851	45	45	(IEA, 2024)
46	2023	\$	304.702	318.851	48	48	(IEA, 2024)
52	2023	\$	304.702	318.851	54	54	(IEA, 2024)
140	2023	\$	304.702	318.851	147	147	(IEA, 2024)
145	2023	\$	304.702	318.851	152	152	(IEA, 2024)
149	2023	\$	304.702	318.851	156	156	(IEA, 2024)
158	2023	\$	304.702	318.851	165	165	(IEA, 2024)
56	2023	\$	304.702	318.851	59	59	(IEA, 2024)

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Original price	Year	Currency	Inflation index	Inflation index 2025	Inflated price	Exchanged price	Reference
65	2023	$	304.702	318.851	68	68	(IEA, 2024)
73	2023	$	304.702	318.851	76	76	(IEA, 2024)
89	2023	$	304.702	318.851	93	93	(IEA, 2024)
135	2023	$	304.702	318.851	141	141	(IEA, 2024)
160	2023	$	304.702	318.851	167	167	(IEA, 2024)
175	2023	$	304.702	318.851	183	183	(IEA, 2024)
200	2023	$	304.702	318.851	209	209	(IEA, 2024)
40	2023	$	304.702	318.851	42	42	(IEA, 2024)
65	2023	$	304.702	318.851	68	68	(IEA, 2024)
110	2023	$	304.702	318.851	115	115	(IEA, 2024)
160	2023	$	304.702	318.851	167	167	(IEA, 2024)
6	2023	$	304.702	318.851	6	6	(IEA, 2024)
17	2023	$	304.702	318.851	18	18	(IEA, 2024)
47	2023	$	304.702	318.851	49	49	(IEA, 2024)
180	2023	$	304.702	318.851	188	188	(IEA, 2024)
205	2023	$	304.702	318.851	215	215	(IEA, 2024)
250	2023	$	304.702	318.851	262	262	(IEA, 2024)
90	2023	$	304.702	318.851	94	94	(IEA, 2024)
125	2023	$	304.702	318.851	131	131	(IEA, 2024)
15	2023	$	304.702	318.851	16	16	(IEA, 2024)
25	2023	$	304.702	318.851	26	26	(IEA, 2024)
35	2023	$	304.702	318.851	37	37	(IEA, 2024)
55	2023	$	304.702	318.851	58	58	(IEA, 2024)
245M	2013	€	99.47	131.921	324.93M	367M	(Hills et al., 2016)
350M	2013	€	99.47	131.921	464.19M	525M	(Hills et al., 2016)
85M	2013	€	99.47	131.921	112.73M	127M	(Hills et al., 2016)
107M	2013	€	99.47	131.921	141.9M	160M	(Hills et al., 2016)
65.6	2008	€	90.32	131.92	95.66	108	(Barker et al., 2008)
129.4	2008	€	90.32	131.92	188.69	213	(Barker et al., 2008)
81.6	2008	€	90.32	131.92	118.99	134	(Barker et al., 2008)
37.3	2008	€	90.32	131.92	54.48	62	(Barker et al., 2008)
72.2	2008	€	90.32	131.92	105.45	119	(Barker et al., 2008)
46.4	2008	€	90.32	131.92	67.77	77	(Barker et al., 2008)
13	2017	€	101.40	131.92	17	19	(Roussanaly et al., 2021)
35	2017	€	101.40	131.92	46	51	(Roussanaly et al., 2021)
40	2017	€	101.40	131.92	52	59	(Roussanaly et al., 2021)
11.5	2017	€	101.40	131.92	15	17	(Roussanaly et al., 2021)
30	2017	€	101.40	131.92	39	44	(Roussanaly et al., 2021)
6	2017	€	101.40	131.92	52	9	(Roussanaly et al., 2021)
15	2017	€	101.40	131.92	20	22	(Roussanaly et al., 2021)
31	2017	€	101.40	131.92	40	46	(Roussanaly et al., 2021)
5	2017	€	101.40	131.92	7	7	(Roussanaly et al., 2021)

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Original price	Year	Currency	Inflation index	Inflation index 2025	Inflated price	Exchanged price	Reference
23	2017	€	101.40	131.92	30	34	(Roussanaly et al., 2021)
4.5	2017	€	101.40	131.92	6	7	(Roussanaly et al., 2021)
11	2017	€	101.40	131.92	14	16	(Roussanaly et al., 2021)
20.5	2017	€	101.40	131.92	27	30	(Roussanaly et al., 2021)
19.5	2017	€	101.40	131.92	25	29	(Roussanaly et al., 2021)
20	2017	€	101.40	131.92	26	29	(Roussanaly et al., 2021)
21	2017	€	101.40	131.92	27	31	(Roussanaly et al., 2021)
28	2017	€	101.40	131.92	36	41	(Roussanaly et al., 2021)
18	2017	€	101.40	131.92	23	26	(Roussanaly et al., 2021)
18.5	2017	€	101.40	131.92	24	27	(Roussanaly et al., 2021)
22	2017	€	101.40	131.92	29	32	(Roussanaly et al., 2021)
13.5	2017	€	101.40	131.92	18	20	(Roussanaly et al., 2021)
15.5	2017	€	101.40	131.92	20	23	(Roussanaly et al., 2021)
17	2017	€	101.40	131.92	22	25	(Roussanaly et al., 2021)
18.5	2017	€	101.40	131.92	24	27	(Roussanaly et al., 2021)
12.5	2017	€	101.40	131.92	16	18	(Roussanaly et al., 2021)
14.5	2017	€	101.40	131.92	19	21	(Roussanaly et al., 2021)
16	2017	€	101.40	131.92	21	24	(Roussanaly et al., 2021)
17.5	2017	€	101.40	131.92	23	26	(Roussanaly et al., 2021)

Year	**HICP**
2006	86.99
2007	88.36
2008	90.32
2009	91.20
2010	92.05
2011	94.32
2012	96.99
2013	99.47
2014	99.79
2015	100.00
2016	100.11
2017	101.40
2018	103.02
2019	105.78
2020	106.96
2021	109.98
2022	122.78
2023	127.81
2024	131.92

Table B.1: HICP for the Euro 2015 = 100 (Central Bureau for Statistics, 2025)

Year	**CPI**
2004	188.9
2005	195.3
2006	201.6
2007	207.342
2008	215.303
2009	214.537
2010	218.056
2011	224.939
2012	229.594
2013	232.957
2014	236.736
2015	237.017
2016	240.007
2017	245.120
2018	251.107
2019	255.657
2020	258.811
2021	270.970
2022	292.655
2023	304.702
2024	313.689
2025	318.851

Table B.2: CPI USD (U.S. Bureau of Labor Statistics, 2025b).

Appendix C

Production Plants Case Study

Table C.1: Production plant specific data of the case study Heidelberg Materials (Tkachenko et al., 2023).

City	Country	Region	Latitude	Longitude	Capacity (Mt)
Gent	Belgium	Europe	51.152206	3.786993	1.5
Ouagadougou	Burkina Faso	Africa	12.445571	-1.50022	0.9
Narayanganj District	Bangladesh	Asia	23.71286	90.51543	3
Chittagong	Bangladesh	Asia	22.279538	91.795684	1.7
Kakanj	Bosnia and Herzegovina	Europe	44.116891	18.113319	0.4
Mukim Serasa	Brunei Darussalam	Asia	5.012333	115.064836	0.5
Argenteuil	Canada	Americas	45.768479	-74.613848	0.3
Prince Edward	Canada	Americas	44.054274	-77.121345	2.2
Edmonton	Canada	Americas	53.580487	-113.600661	1.38
Delta	Canada	Americas	49.143998	-123.023077	1.356
Lukala	Congo, Democratic Republic of the	Africa	-5.50852	14.526127	0.3
Luhihi	Congo, Democratic Republic of the	Africa	-2.256797	28.871808	0.15
Tanganyika	Congo, Democratic Republic of the	Africa	-5.555034	29.341047	0.05
Sivice	Czechia	Europe	49.215622	16.773065	1.4
Hannover	Germany	Europe	52.374756	9.876779	0.9
Cairo Governorate Desert	Egypt	Africa	29.919723	31.53258	5
Suez Desert	Egypt	Africa	29.769909	32.211601	4.2
Tura	Egypt	Africa	29.926087	31.301513	4.625
Kunda	Estonia	Europe	59.496786	26.5284	0.75
Airvault	France	Europe	46.809772	-0.138968	1.5
Bussac-Forêt	France	Europe	45.226037	-0.365494	0.6
Cruas	France	Europe	44.642952	4.754983	1.8
Villiers-au-Bouin	France	Europe	47.587909	0.328983	1.2
Beffes	France	Europe	47.083275	3.002822	1.6
Lancashire	United Kingdom	Europe	53.888913	-2.383373	1.3

Continued on next page

Table C.1 – continued from previous page

City	Country	Region	Latitude	Longitude	Capacity (Mt)
Flintshire	United Kingdom	Europe	53.152678	-3.061635	1.7
Ketton	United Kingdom	Europe	52.640356	-0.547016	2.3
Rustavi	Georgia	Asia	41.513089	45.047818	1.2
Takoradi	Ghana	Africa	4.891983	-1.745828	2.2
Beremend	Hungary	Europe	45.810911	18.39875	1.5
Bogor	Indonesia	Asia	-6.479811	106.899118	20.5
Cirebon	Indonesia	Asia	-6.705337	108.401523	4.1
Kotabaru Regency	Indonesia	Asia	-3.271007	116.105835	2.6
Tumkur	India	Asia	13.27022	76.723122	1.5
Narsinghgarh	India	Asia	23.990282	79.392584	5.5
Donda Padu	India	Asia	16.832064	80.036823	3
Bachaoli Khurd	India	Asia	25.499517	78.711436	2.4
Puzhuthivakkam	India	Asia	13.260661	80.306354	1
Auj Aherwadi	India	Asia	17.540668	76.034869	0.95
Provincia di Matera	Italy	Europe	40.674977	16.657804	1.5
Italcementi	Italy	Europe	39.470522	9.024111	0.9
San Giovanni	Italy	Europe	42.464	13.258323	2
Tavernola Bergamasca	Italy	Europe	45.716549	10.047122	1.5
Provincia di Cosenza	Italy	Europe	39.834649	16.246287	1.2
Provincia di Salerno	Italy	Europe	40.660936	14.869269	1.5
Provincia di Campobasso	Italy	Europe	41.456132	14.551073	1.4
Area Industriale	Italy	Europe	44.475979	12.253358	1
Mangystau District	Kazakhstan	Asia	44.089136	52.120629	0.8
Zyryan District	Kazakhstan	Asia	49.64296	83.575126	1.5
Taroudant	Morocco	Africa	30.220295	-9.15274	2.2
Safi	Morocco	Africa	32.552532	-9.104544	1
Marsa	Morocco	Africa	27.077753	-13.418374	0.5
Narvik	Norway	Europe	68.094529	16.375326	0.5
Porsgrunn	Norway	Europe	59.062104	9.69024	1.8
Powiat krapkowicki	Poland	Europe	50.534264	17.977889	1.1
D browa Górnicza	Poland	Europe	50.353406	19.269223	2.2
Chi c daga	Romania	Europe	45.95512	22.8678	1.8
Slantsy	Russian Federation	Asia	59.112037	28.191385	1.2
Aleksinsky District	Russian Federation	Asia	54.482932	37.341077	2
Slite	Sweden	Europe	57.710068	18.804074	2.5
Yoto	Togo	Africa	6.621423	1.573569	1.5
Lomé	Togo	Africa	6.153305	1.2881	0.75
Kozah	Togo	Africa	9.459846	1.221515	0.25
Ladik	Turkey	Asia	40.935634	35.884591	1
Ezine	Turkey	Asia	39.865142	26.244503	1
Songwe	Tanzania, United Republic of	Africa	-8.942343	33.241146	1.2
Dar es Salaam	Tanzania, United Republic of	Africa	-6.662689	39.166959	2

Continued on next page

Table C.1 – continued from previous page

City	Country	Region	Latitude	Longitude	Capacity (Mt)
Logansport	United States of America	Americas	40.734706	-86.43344	1
Mitchell	United States of America	Americas	38.738901	-86.456875	0.6
Redding	United States of America	Americas	40.736884	-122.32239	0.5
Tehachapi	United States of America	Americas	35.122944	-118.369208	0.1
Union Bridge	United States of America	Americas	39.560503	-77.171631	0.4
Bellingham	United States of America	Americas	48.768488	-122.524762	0.7
Catskill	United States of America	Americas	42.140334	-73.913151	2.5

Appendix D

Transport and Storage

Besides investing in carbon capture technology, it is also necessary to transport and store the captured carbon. Potential storage sites were identified using the dataset compiled by the IEA (2025). To ensure reliability, only sites with an operational or under-construction status were included, thus minimising the risk that planned facilities might not come to fruition once investments are made.

It is assumed that, for each capture facility, transport and storage will occur at the lowest-cost site. To determine these costs, first, the average per tontransport and storage cost is assembled from estimates in the literature, taking into account transport mode (pipeline, ship, or truck) and annual carbon volume, since larger throughput typically reduces unit costs. For each supplier, the total cost comprises two or three components:

1. Cost of moving carbon from the capture site to the nearest pipeline, harbour or storage facility.
2. Cost of injecting carbon into the selected storage site.
3. Additional shipping costs when no suitable storage site is nearby[1].

For the costs of transporting carbon via an onshore pipeline, the data is retrieved from Figure 9 of the paper of Roussanaly et al. (2021). The values are presented in Table D.1. The values are inflated and exchanged as can be found in Appendix B.

Onshore pipeline transport costs are taken from Figure 9 in (Roussanaly et al., 2021), inflated and currency-converted as detailed in Appendix B. The resulting values appear in Table D.1.

Annual carbon flowrate	100km	250km	500km
0.25	19	51	-
0.5	17	44	-
1	9	22	46
1.5	7	17	34
2	7	16	30

Table D.1: Carbon transport cost for onshore pipeline (Roussanaly et al., 2021)

The costs for shipping carbon between harbours are retrieved from Roussanaly et al. (2021) as well. They are read from Figure 12 and shown in Table D.2. The values are inflated and exchanged as can be found in Appendix B.

[1] e.g., for African suppliers, an extra maritime leg from the nearest port to a North Sea or a United States storage port is included.

Annual carbon flowrate	100km	250km	500km	750km	1000km
0.25	29	29	31	41	41
0.5	22	26	27	31	32
1	20	23	25	27	29
1.5	18	21	24	26	29
2	18	21	23	25	26

Table D.2: Carbon transport cost between harbours (Roussanaly et al., 2021)

To estimate the cost of carbon transport between harbours via ship, cost data were available for five distinct annual flow rates over a distance range of 100 km to 1000 km. However, the model requires cost estimates for harbour pairs separated by distances exceeding this range. To address this limitation, a logarithmic regression function was fitted to the available data for each flow rate. This method is based on the assumption that transport costs increase with distance in a non-linear fashion, rising more steeply at shorter distances and gradually levelling off as distance increases. The resulting regression curves were used to extrapolate cost values beyond 1000 km, thereby extending the dataset to cover longer shipping routes. A separate regression formula was derived for each annual carbon flow rate and is presented below. For distances shorter than 100 km, the cost corresponding to 100 km was applied, assuming that short-distance cost behaviour follows a similar pattern. Also, from the 6000km, the costs will stay the same for larger distances.

$$y_{0.25} = 5.6759ln(x) + 0.2930 \tag{D.1}$$

$$y_{0.5} = 4.2474ln(x) + 2.2267 \tag{D.2}$$

$$y_1 = 4.3471ln(x) + -5.1687 \tag{D.3}$$

$$y_{1.5} = 4.5337ln(x) + -3.4837 \tag{D.4}$$

$$y_2 = 3.4569ln(x) + 1.9491 \tag{D.5}$$

From Myers et al. (2024), the cost estimates for transporting carbon by truck tanker are obtained. The analysis considers only the truck tanker transport mode. According to Figure 3(c) in the source, labour costs account for approximately 21.7% of the total transportation cost. To account for regional cost variation, average labour costs for the countries in which the cement plants are located were collected. Based on this information, countries with lower average labour costs are assumed to have proportionally lower overall transportation costs. Same for countries with higher labour costs on average. This adjustment was incorporated by scaling the transport cost component attributable to labour according to the relative national labour cost levels. The resulting country-specific adjustments ensure more accurate cost estimates and are based on the labour cost data presented in Table D.4. Where country-specific labour cost data were unavailable, the labour cost was assumed to match that of the nearest country with available data.

Annual carbon flowrate	16km	160km	320km	480km	640km	800km
0.05	68	82	100	127	147	165
0.1	43	57	75	103	122	138
0.2	31	43	62	87	106	125
1	25	31	55	81	100	115

Table D.3: Carbon transport cost via Tanker truck (USA average) in 2024 USD (Myers et al., 2024)

Cost estimates have been adjusted for inflation where dates were available; in the absence of a date, the original value was retained. The base transportation costs across various annual carbon flow rates and distances are presented in Table D.3 and were derived from Figure 3(a) of the original study.

For truck-based carbon transport, it is assumed that if a facility is located within a 5km radius of a port, the transport costs to the port can be considered negligible. Facilities located between 5 km and 10 km from a port are assigned the cost corresponding to a 16 km transport distance, reflecting the shortest available range in the dataset. To estimate transport costs for routes exceeding 800 km, a linear regression model was developed for each annual carbon flow rate. These regression formulas, presented below, are based on the available data and allow for extrapolation beyond the original distance range. This approach enables the estimation of carbon transport costs by truck for long-distance routes not explicitly covered in the source data.

$$y_{0.05} = 0.1282x + 63.2201 \tag{D.6}$$

$$y_{0.1} = 0.1265x + 38.7168 \tag{D.7}$$

$$y_{0.2} = 0.1240x + 25.7230 \tag{D.8}$$

$$y_{1} = 0.1239x + 17.9365 \tag{D.9}$$

For storage cost in the United States, the cost data was retrieved from Smith et al. (2021). In Table 3 of the paper, they show the storage costs for three scenarios, namely, low, mean, and high, under base monitoring assumptions. This thesis assumes a mean storage cost. That is for a rate Mtpa carbon of 1 \$16.47 and for a rate Mtpa carbon of 3.2 \$8.00 (2019\$/tCO_2).

D.1 Storage Locations

The Edmonton facility in Alberta, Canada, is connected to a 240 km onshore carbon pipeline (Enhance Energy Inc. and Wolf Midstream, 2025). Transport costs for this route are based on the 250 km distance category in Table D.1.

The Weyburn–Beulah system comprises a 320 km pipeline linking Beulah, North Dakota, to the Weyburn storage site in Saskatchewan (Preston et al., 2005). Cost increments between the 100–250 km and 250–500 km categories scale approximately linearly with distance; applying a factor of 1.28 (320 km divided by 250 km) to the 250 km cost estimates yields per tonvalues of 65, 56, 28, 22 and 20 for the relevant pipeline components. Up-front carbon delivery to the Beulah trunk, whether by truck or local pipeline, is priced at the same per-kilometre rate.

In the North Sea region, the Port of Rotterdam's Porthos project (Porthos CO_2 Transport and Storage C.V., 2025), the Teesside and Humber schemes in the UK (Genesis Energies, 2022), and Norway's Full-scale CCS initiative (Gassnova SF and DNV GL Energy, 2020; Røsjorde & Carpenter, n.d.) all employ identical transport and storage tariffs, derived from the Norwegian project's cost model. When a capture facility lies inland, additional charges are added for overland delivery to the nearest North Sea port (defined between latitudes 50°–70° N and longitudes –2.5°–20° E), or for shipment via an intermediate port before final delivery to North Sea storage.

Overall transport-plus-storage costs in this region are approximately $80 per ton for a 0.8 Mtpa operation, and $40 per ton for 1.5 Mtpa capacity (Røsjorde & Carpenter, n.d.). No publication date was available for these figures, so no inflation adjustment has been applied.

Country	Average labour costs (USD)	Source
Belgium	59.3	(International Labour Organization, n.d.)
Burkina Faso	2.14	-
Bangladesh	1.26	(Shaik, 2025)
Bosnia and Herzegovina	3.39	("Average Salary in Bosnia and Herzegovina", 2024)
Brunei Darussalam	0.0026	-
Canada	38.97	("Statistics on labour costs", 2024a)
Congo, Democratic Republic of the	1.42	("What is the average salary in Africa?", 2023)
Czechia	27.39	("Statistics on labour costs", 2024b)
Germany	58.43	("Statistics on labour costs", 2024b)
Egypt	2.44	(Uppala, 2024)
Estonia	26.66	("Statistics on labour costs", 2024b)
France	56.73	("Statistics on labour costs", 2024b)
United Kingdom	29.04 [2]	("Statistics on labour costs", 2024b)
Georgia	10.01	("Statistics on labour costs", 2024b)
Ghana	2.14	("What is the average salary in Africa?", 2023)
Hungary	27.38	("Statistics on labour costs", 2024b)
Indonesia	0.0026	(ERI Economic Research Institute, 2025)
India	2.27	(Partnership, 2024)
Italy	44.28	("Statistics on labour costs", 2024b)
Kazakhstan	17.62	("Statistics on labour costs", 2024b)
Morocco	11.37	("What is the average salary in Africa?", 2023)
Norway	63.03	("Statistics on labour costs", 2024b)
Poland	33.99	("Statistics on labour costs", 2024b)
Romania	28.27	("Statistics on labour costs", 2024b)
Russian Federation	0.09	("Statistics on labour costs", 2024b)
Sweden	48.73	("Statistics on labour costs", 2024b)
Togo	2.14	-
Turkey	2.14	("Statistics on labour costs", 2024b)
Tanzania, United Republic of	0.1	("What is the average salary in Africa?", 2023)
United States of America	55.75	(Myers et al., 2024)

Table D.4: Average labour costs per country.

Appendix E

Regional and Subregional Coordinates

The coordinates used at the subregional and regional levels for calculating transportation costs are shown in Table E.1.

(Sub)region	**Coordinates**
Middle Africa	(7, 21)
Western Africa	(13, -2)
Eastern Africa	(3, 39)
Northern Africa	(27, 15)
Southern Africa	(30, 25)
Africa	(9, 18)
Southern Asia	(25, 76)
Eastern Asia	(37, 108)
Central Asia	(44, 74)
South-Eastern Asia	(1, 111)
Western Asia	(29, 49)
Asia	(34, 101)
Western Europe	(50, 3)
Southern Europe	(43, 12)
Eastern Europe	(51, 25)
Northern Europe	(59, 12)
Europe	(53, 9)
Caribbean	(15, -76)
Northern America	(48, 100)
South America	(14, 59)
Central America	(12, -86)
Americas	(12, -86)
Oceania	(-30, 140)

Table E.1: Approximate geographic coordinates of (sub)regions.

Appendix F

Transportation Cost Data Processing

This appendix provides a detailed description of the pre-processing steps performed on transportation cost data sourced from *UNCTAD's Transport Costs* dataset (United Nations Conference on Trade and Development, 2024). Transport costs are extracted at the subregional level by filtering for:

- **Product:** Portland cement, aluminous cement (ciment fondu), slag cement, supersulphate cement and similar hydraulic cements, whether or not coloured or in the form of clinkers.
- **Transport mode:** All modes,
- **Indicator:** Per-unit freight rate ($/kg),
- **Reporting level:** Subregion-to-subregion trade.
- **Year:** 2021.

F.1 UNCTAD Cost Matrix

When the transportation-cost matrix was first inspected, several origin-to-destination entries appeared blank, indicating missing data for specific shipping routes. To ensure comprehensive coverage, a hierarchical, two-stage filling method was applied.

Each subregion belongs to a larger parent region (for example, Western Europe under Europe, Northern Africa under Africa). Whenever a subregion's shipping cost was absent, the corresponding cost to its parent region was used instead. This straightforward substitution filled many gaps, since parent-region values tend to be more complete.

Remaining blanks often occurred in less-reported areas where even parent-region values were missing. These were addressed by organising all regions into five continental clusters – Africa, the Americas, Asia, Europe, and Oceania. For any lingering empty entry (for instance, shipping from East Africa to Northern Europe), the average cost to all other subregions in the same cluster (Eastern, Southern, and Western Europe) was calculated and applied. This mirrors the expectation that shipping costs into one part of a continent approximate those into its neighbouring parts.

Finally, all freight-rate figures were multiplied by 1000 to convert from $/kg to $/ton, ensuring consistency with the unit conventions adopted in the modelling framework.

In cases where no sibling subregion within a cluster provided data for a particular origin, a placeholder value of 10,000 was assigned. This conspicuously large number results in the route not being a viable option.

By layering parent-region substitution, continental-cluster averaging, and an explicit large placeholder for truly absent data, the once-sparse matrix becomes fully populated. Every origin-destination pair now carries a value, ensuring that downstream analyses and models operate on a complete set of transportation-cost estimates, with clear traceability for each imputed figure.

F.2 Distance-Adjusted Subregion Freight Cost Estimation

Within the model, the parameter τ_{ij} – which represents the transportation cost between supplier node i and customer node j – is calculated in two steps. First, each node is assigned to its UNCTAD subregion (e.g. Western Europe, Eastern Europe), and the baseline cost is retrieved from the outlier-corrected freight-rate matrix, discussed in section F.1. This matrix entry reflects the average cost of shipping between the two subregions.

If both i and j lie in the same subregion, τ_{ij} is simply set equal to that baseline cost, with no further adjustment. When i and j belong to different subregions, a distance adjustment is applied to account for the difference between the actual node-to-node separation and the assumed centroid-to-centroid distance of the subregions. The distance d_{ij} between nodes i and j is computed, and the centroid distance $d_{R_iR_j}$ between their respective subregions. These coordinates are provided in Appendix E. The per-kilometre rate r is then defined as the subregion-pair cost ($c_{R_iR_j}$) divided by the distance between the subregion-pair, as shown in Equation F.1.

$$r = \frac{c_{R_iR_j}}{d_{R_iR_j}} \tag{F.1}$$

The distance difference $\Delta D = d_{ij} - d_{R_iR_j}$ is multiplied by the rate to yield the adjustment term. If $\Delta D > 0$, nodes farther apart than their centroids, this term is added to the baseline; if $\Delta D < 0$, nodes closer to each other, it is subtracted. Formally:

$$\tau_{ij} = c_{R_iR_j} + r \cdot \Delta D \tag{F.2}$$

This hybrid approach ensures that τ_{ij} captures both the statistically robust average inter-subregion tariff and the geographic separation of the two nodes, yielding a continuous, distance-sensitive cost input for the model.

Appendix G

Carbon Capture Investment and Price Assumptions

Due to the limited availability of specific data on investment and production costs related to carbon capture technologies, assumptions were made based on available literature. Sensitivity analysis will be conducted to evaluate the impact of uncertainties surrounding these assumptions. It is assumed that

For cement production costs without carbon capture technology, the following regional average operational costs per ton of cement were assumed based on the estimates provided by Cook (2009): OECD countries $45, Asia $20, Latin America $24, North America $42.5, Africa $42.5, and Middle East countries $42.5. It is explicitly assumed that these values represent only operational expenses, including raw materials, fuel, labour, and maintenance, and exclude any capital expenses. It is assumed that the production cost for Europe is the same as the production cost for the OECD countries. The ratio between the regions can be computed using these production costs and are presented in Table G.2.

Region	**Ratio**
OECD countries (& Europe)	1
Asia	0.444
Latin America	0.533
North America	0.944
Africa	0.944
Middle East	0.944

Table G.1: Ratios between production costs of Cook (2009).

Cost estimates for production without carbon capture, as well as for post-combustion and oxy-combustion capture at European and Asian plants, are provided by Barker et al. (2008). These estimates are adjusted for inflation and converted to USD as detailed in Appendix B, and subsequently regionalised using the ratios presented in Table G.2.

Investment cost estimates for post-combustion carbon capture technology were derived from multiple sources (Barker et al., 2008; Gerbelová et al., 2017; Hegerland et al., 2006; Hills et al., 2016). Based on these studies, the capital investment for retrofitting a cement plant with post-combustion technology is assumed to range between $367 million and $525 million.

Similarly, capital investment costs for retrofitting partial oxy-fuel combustion technology were estimated to range between $127 million and $160 million (Hills et al., 2016).

Finally, it must be emphasised that the presented investment and operational cost figures are preliminary approximations derived from limited available literature. Cement manufacturers intending to utilise the

Region	No carbon capture (baseline)	Post-combustion	Partial oxy-fuel combustion
OECD countries (& Europe)	108	213	134
Asia	62	119	77
Latin America	58	114	71
North America	102	201	126
Africa	102	201	126
Middle East	102	201	126

Table G.2: Production costs per region.

developed optimisation model should update and tailor these parameters based on their specific operational context and region-specific economic conditions.

G.1 Profit and Revenue Calculation

Each region's cement selling price (revenue) is obtained by applying its profit margin to the region's marginal cost. The marginal cost comprises the production cost, the regional carbon-compliance expense, and the transportation cost per ton of cement. This is expressed as:

$$Revenue_t = (production_{baseline} + transportation_r + 0.8165\theta_{rt})(1 + profit_r) \tag{G.1}$$

where 0.8165 t CO_{2e} denotes the per ton emissions factor (see subsection 4.1.3), θ_{rt} is the carbon price in region r at time t and $transportation_r$ is the average transportation cost in that region. Average profit margins used in the model are:

- Africa: 0.16 (World Economic Forum, 2023)
- Asia: 0.17[1] (Topstock Research, 2025)
- Europe: 0.2 (Panichi et al., 2022)
- North America: 0.16 (World Economic Forum, 2023)
- South America: 0.16 (World Economic Forum, 2023)

[1]This figure is derived from the reported profit margin of UltraTech Cement in India, assuming that profit margins at other Asian operations are broadly comparable.

Appendix H

Results

Table H.1: Facility-level investment decisions indicating the year and location of carbon-reducing technology adoption, reported for each carbon pricing scenario both with and without the CBAM regulation.

Scenario	**Number investments**		**Locations**	
	w/ CBAM	w/o CBAM	w/ CBAM	w/o CBAM
STEPS	10	0	Aleksinsky District '35 Bachaoli Khurd '34 Chittagong '36 Cirbon '31 Donda Padu '33 Kotabaru Regency '29 Narayanganj District '30 Narsinghgarh '32 Puzhuthivakkam '28 Slantsy '38 Tumkur '37	-

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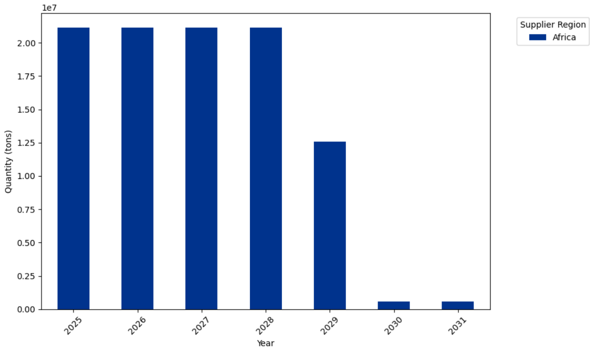
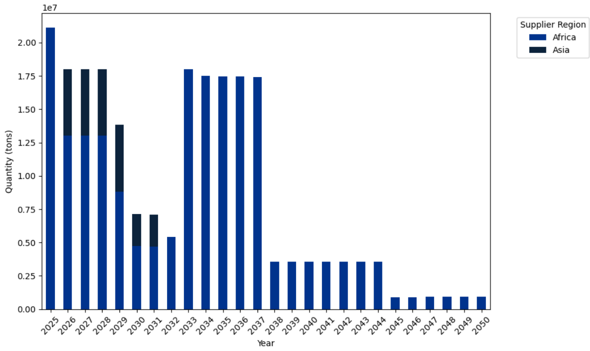
Table H.1 – continued from previous page

Factor	Number investments		Locations	
	w/ CBAM	w/o CBAM	w/ CBAM	w/o CBAM
ASP	17	12	Aleksinsky District ’28 Auj Aherwadi ’27 Bachaoli Khurd ’33 Cirebon ’30 Donda Padu ’31 Ketton ’39 Kotabaru Regency ’29 Mangystau District ’35 Narsinghgarh ’32 Prince Edward ’40 Puzhuthivakkam ’26 Slantsy ’25 Slite ’38 Takoradi ’41 Taroundant ’37 Tumkur ’34 Zyryan District ’36	Aleksinsky District ’41 Bachaoli Khurd ’44 Cirebon ’37 Donda Padu ’39 Gent ’34 Ketton ’28 Kotabaru Regency ’38 Narsinghgarh ’43 Prince Edward ’32 San Giovanni ’35 Slite ’33 Tumkur ’40
NZE	21	20	Aleksinsky District ’25 Auj Aherwadi ’34 Bachaoli Khurd ’32 Catskill ’45 Chi c daga ’46 Cirebon ’28 Cruas ’41 Donda Padu ’30 Flintshire ’42 Gent ’40 Ketton ’37 Kotabaru Regency ’29 Narsinghgarh ’31 Prince Edward ’44 San Giovanni ’39 Slantsy ’26 Slite ’35 Takoradi ’43 Taroundant ’36 Tumkur ’33 Zyryan District ’38	Airvault ’41 Aleksinsky District ’35 Bachaoli Khurd ’34 Beffes ’40 Catskill ’38 Cirebon ’31 Cruas ’37 Donda Padu ’30 Flintshire ’39 Gent ’36 Ketton ’27 Kotabaru Regency ’28 Narsinghgarh ’32 Prince Edward ’44 Puzhuthivakkam ’26 San Giovanni ’42 Slantsy ’29 Slite ’33 Takoradi ’45 Tumkur ’25

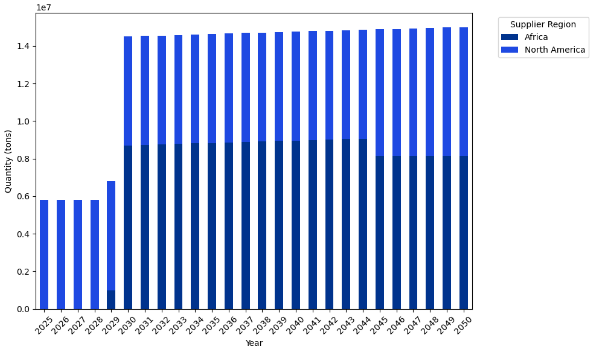
H.1 STEPS Scenario Results



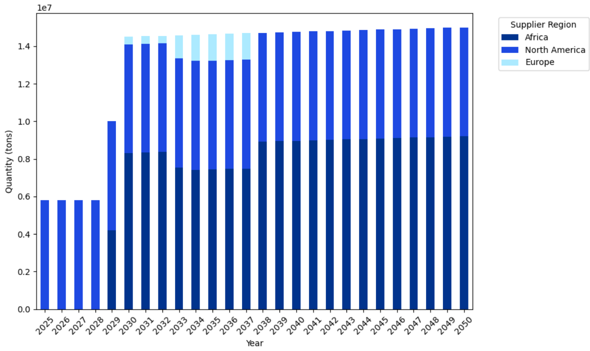
(a) Africa's supply sources by region under STEPS (without CBAM).



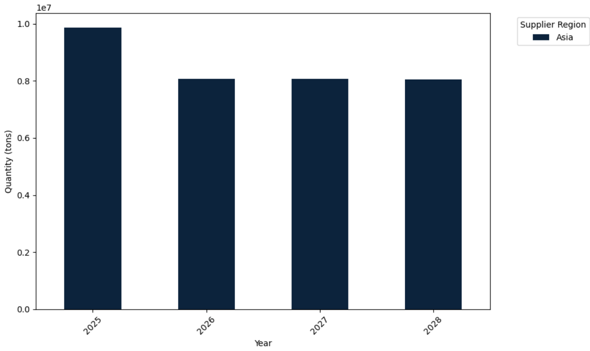
(b) Africa's supply sources by region under STEPS (with CBAM).



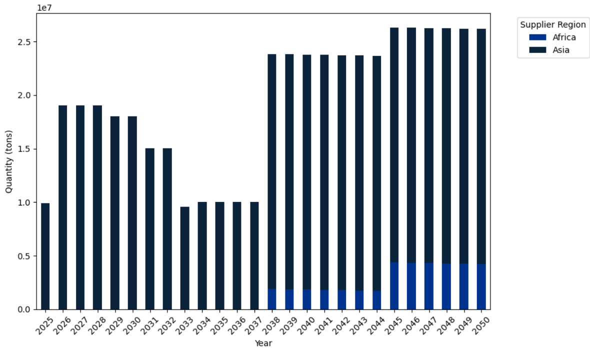
(c) Americas supply sources by region under STEPS (without CBAM).



(d) Americas supply sources by region under STEPS (with CBAM).



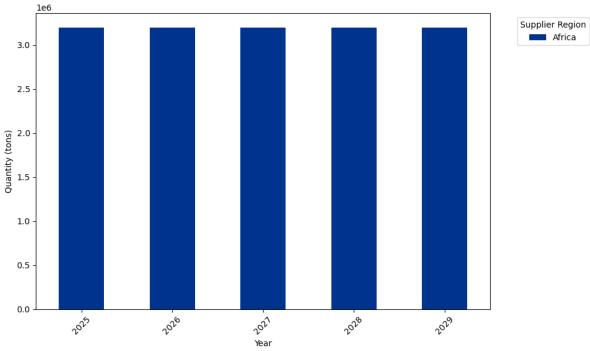
(e) Asia's supply sources by region under STEPS (without CBAM).



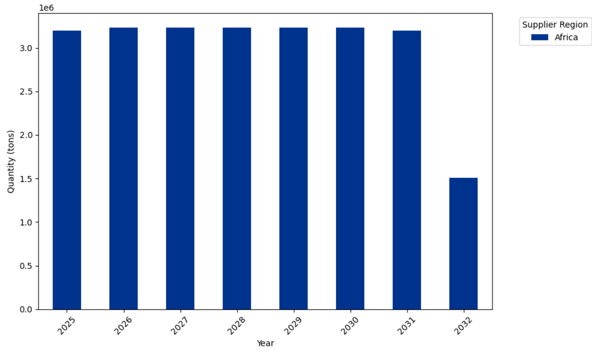
(f) Asia's supply sources by region under STEPS (with CBAM).

Figure H.1: Supply sources by region under STEPS (with CBAM).

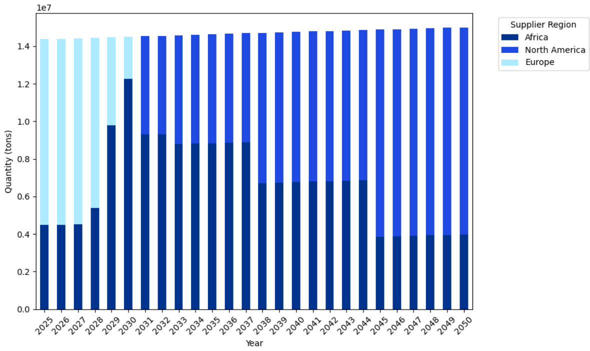
H.2 APS Scenario Results



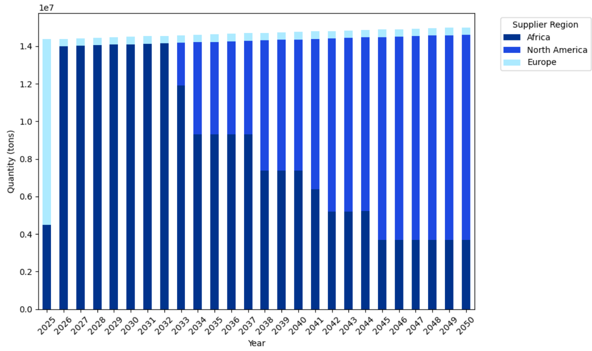
(a) Africa's supply sources by region under APS (without CBAM).



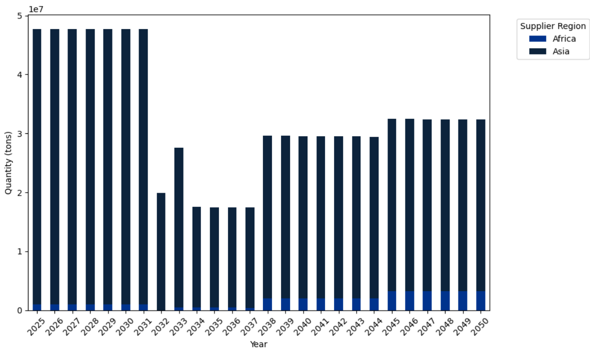
(b) Africa's supply sources by region under APS (with CBAM).



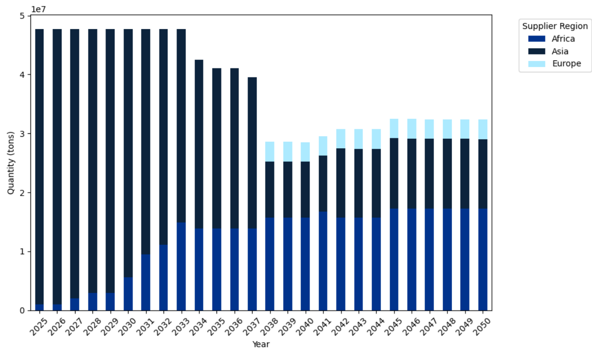
(c) Americas supply sources by region under APS (without CBAM).



(d) Americas supply sources by region under APS (with CBAM).



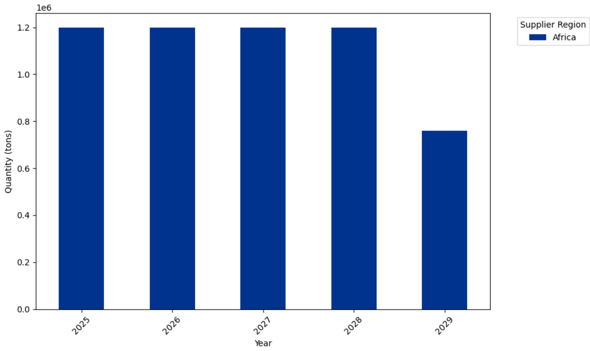
(e) Asia's supply sources by region under APS (without CBAM).



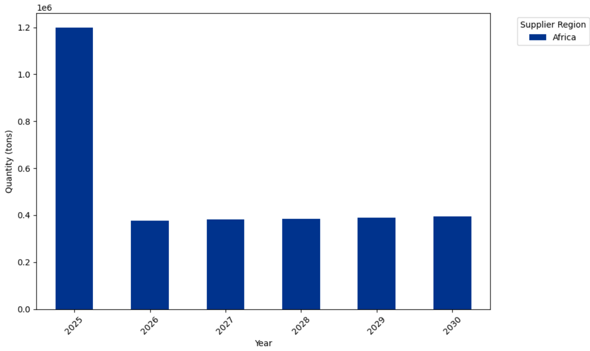
(f) Asia's supply sources by region under APS (with CBAM).

Figure H.2: Supply sources by region under APS (with CBAM).

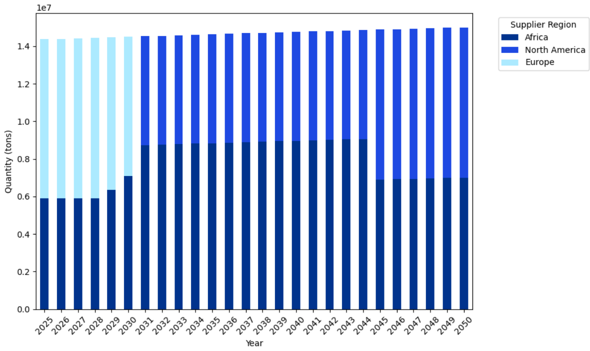
H.3 NZE Scenario Results



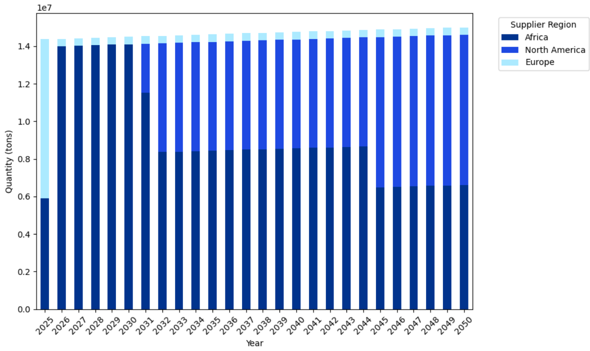
(a) Africa's supply sources by region under NZE (without CBAM).



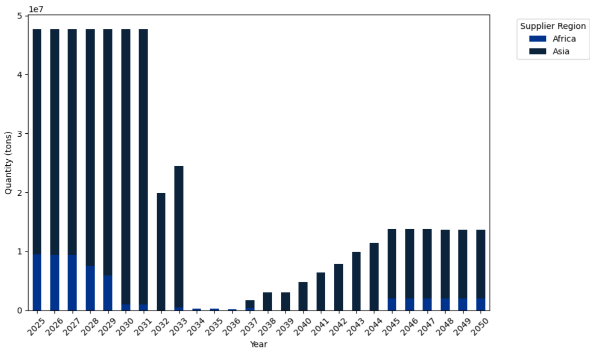
(b) Africa's supply sources by region under NZE (with CBAM).



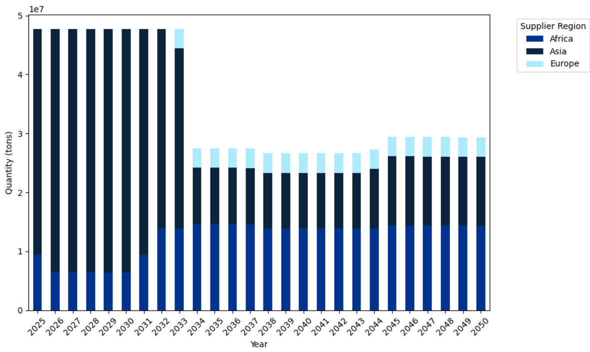
(c) Americas supply sources by region under NZE (without CBAM).



(d) Americas supply sources by region under NZE (with CBAM).



(e) Asia's supply sources by region under NZE (without CBAM).



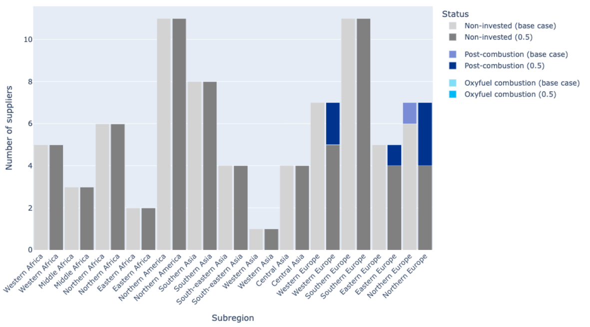
(f) Asia's supply sources by region under NZE (with CBAM).

Figure H.3: Supply sources by region under NZE (with CBAM).

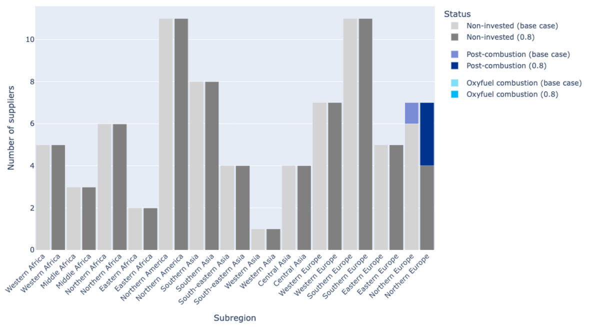
H.4 Sensitivity Analysis Results

H.4.1 Production Costs

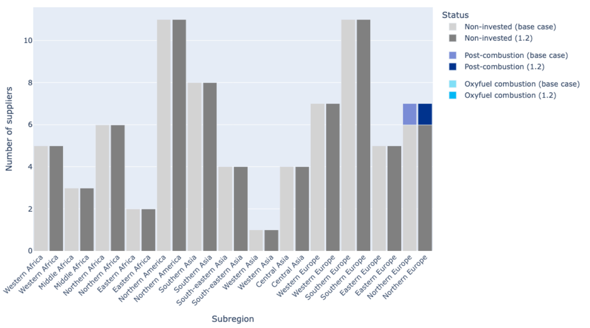
Investment Decisions



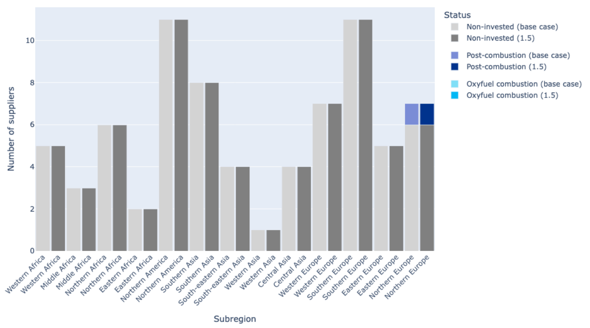
(a) Production cost factor 0.5 (no CBAM).



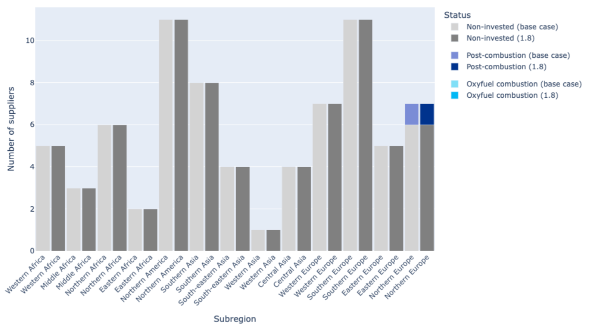
(b) Production cost factor 0.8 (no CBAM).



(c) Production cost factor 1.2 (no CBAM).

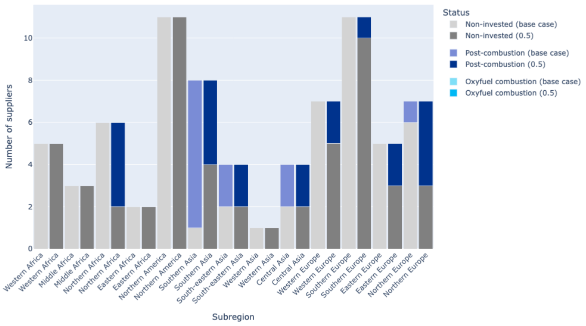


(d) Production cost factor 1.5 (no CBAM).

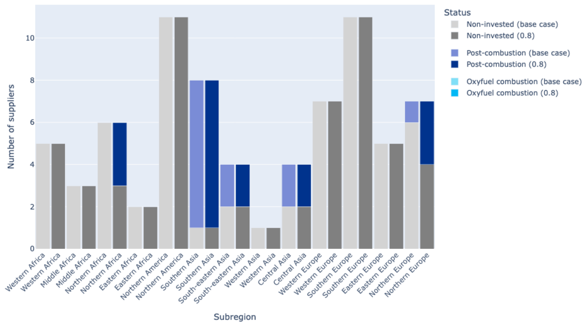


(e) Production cost factor 1.8 (no CBAM).

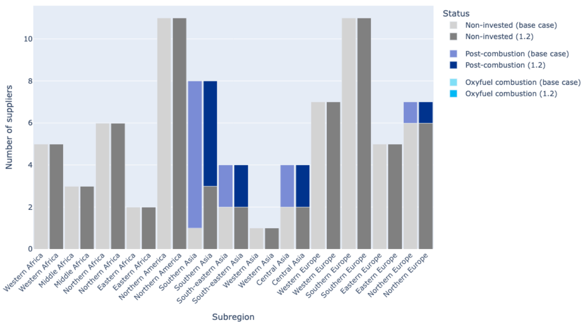
Figure H.4: Investment decisions by subregion under varying production-cost factors, compared to the base case, when CBAM is not applied.



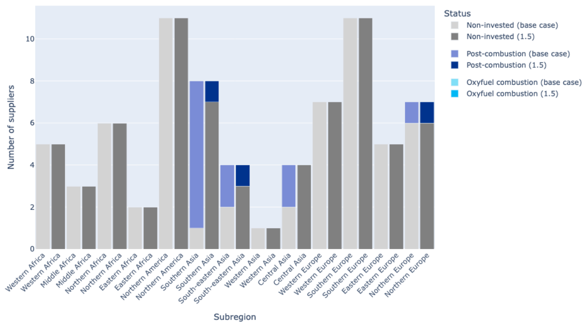
(a) Production cost factor 0.5 (with CBAM).



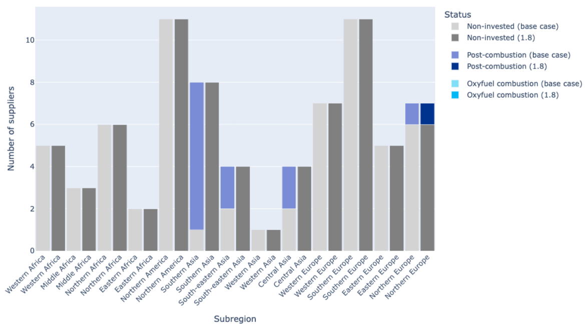
(b) Production cost factor 0.8 (with CBAM).



(c) Production cost factor 1.2 (with CBAM).



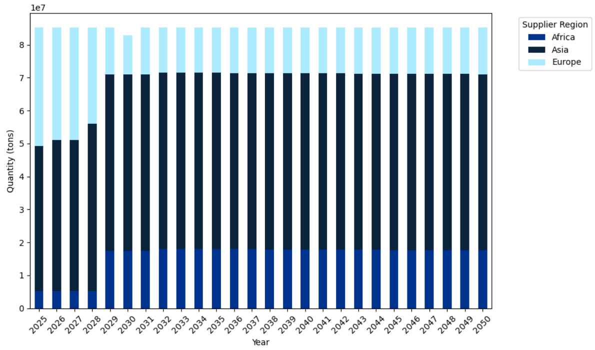
(d) Production cost factor 1.5 (with CBAM).



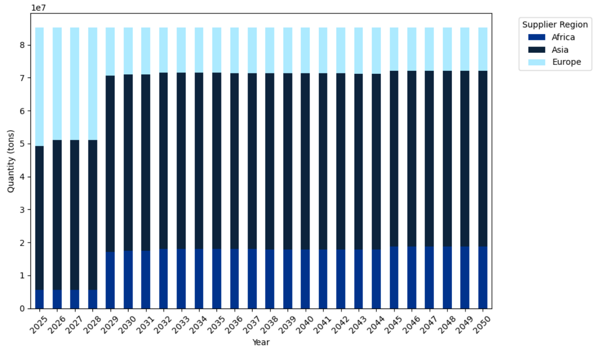
(e) Production cost factor 1.8 (with CBAM).

Figure H.5: Investment decisions by subregion under varying production-cost factors, compared to the base case, when CBAM is applied.

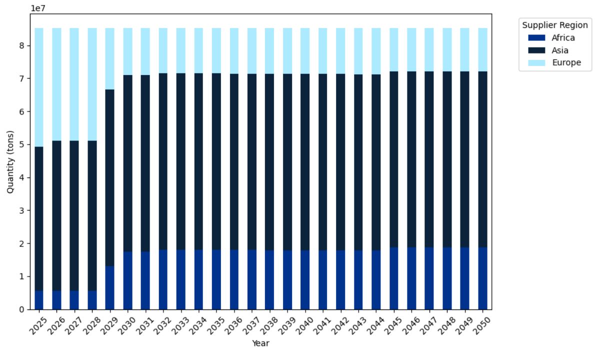
Distribution Shares



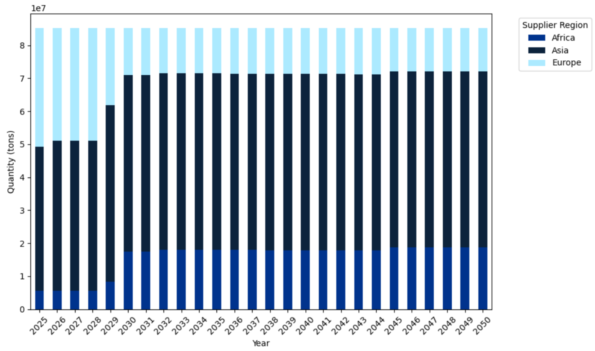
(a) Production costs 0.5 (no CBAM).



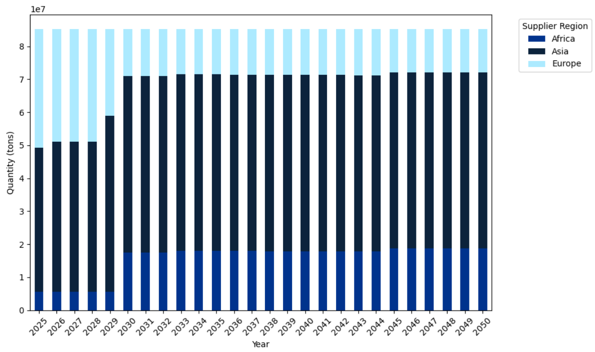
(b) Production costs 0.8 (no CBAM).



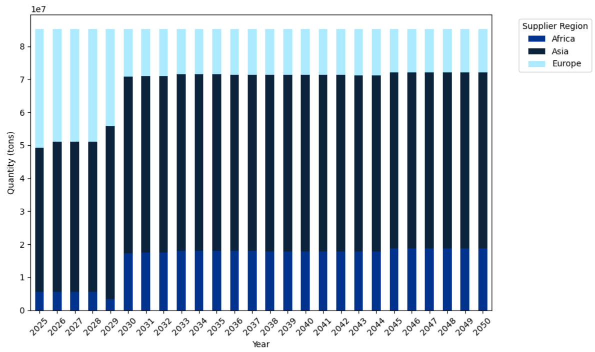
(c) Production costs 1 (no CBAM).



(d) Production costs 1.2 (no CBAM).

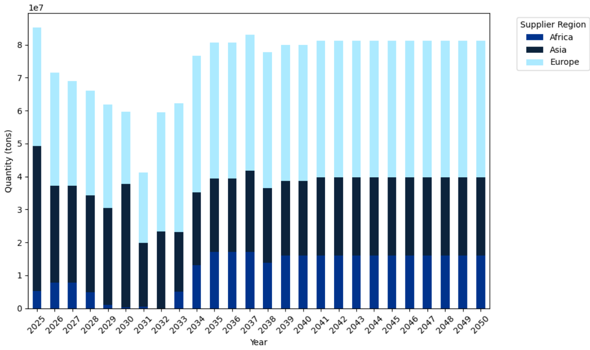


(e) Production costs 1.5 (no CBAM).

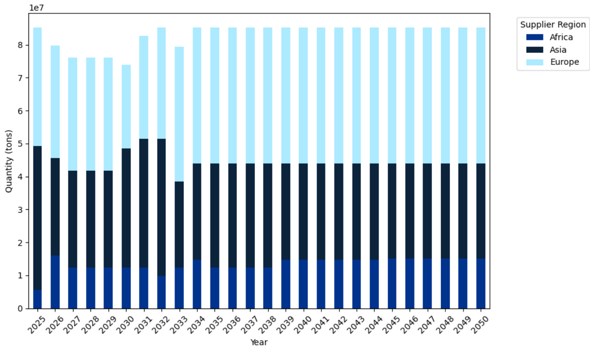


(f) Production costs 1.8 (no CBAM).

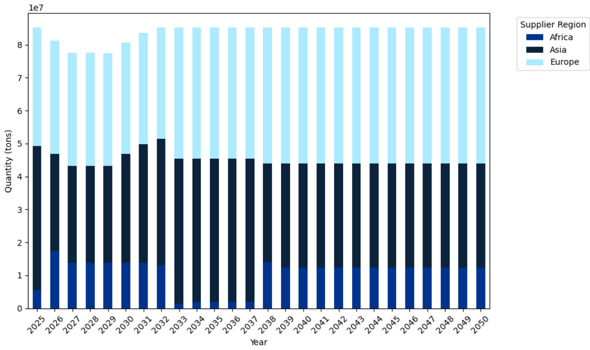
Figure H.6: Cement-supply shares to Europe over time under varying production-cost factors, when CBAM is not applied.



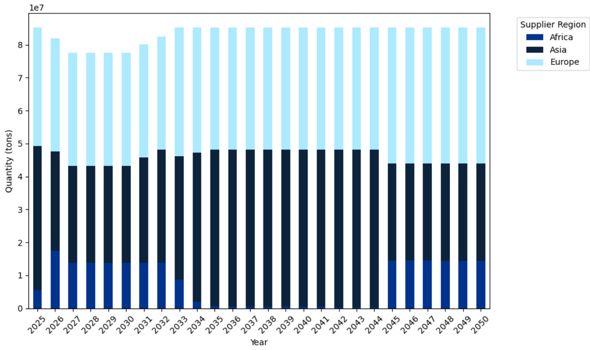
(a) Production cost factor 0.5 (with CBAM).



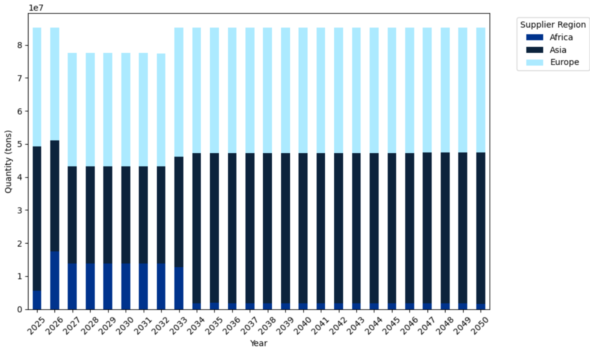
(b) Production cost factor 0.8 (with CBAM).



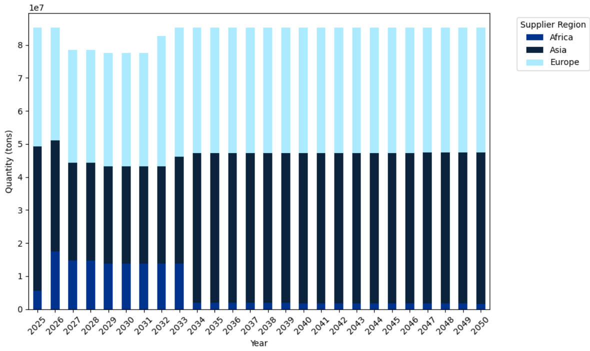
(c) Production cost factor 1 (with CBAM).



(d) Production cost factor 1.2 (with CBAM).



(e) Production cost factor 1.5 (with CBAM).

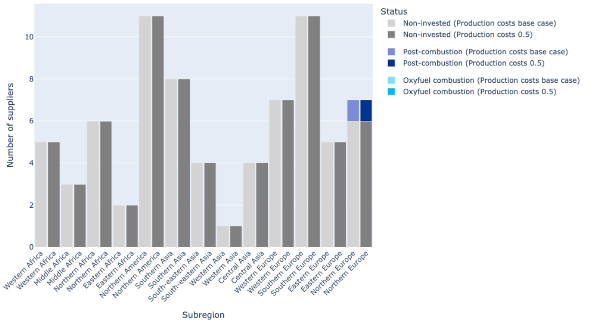


(f) Production cost factor 1.8 (with CBAM).

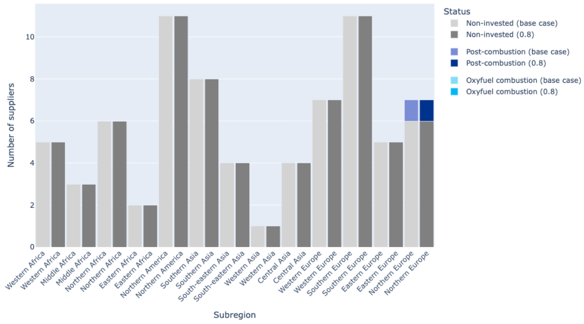
Figure H.7: Cement-supply shares to Europe over time under varying production-cost factors, when CBAM is applied.

H.4.2 Transportation Costs

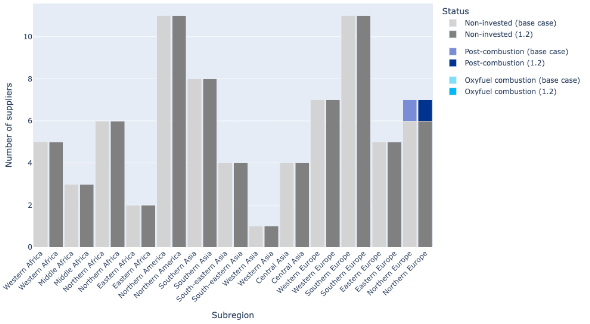
Investment Decisions



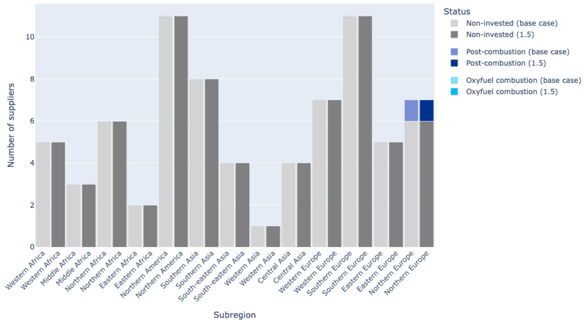
(a) Transportation cost factor 0.5 (no CBAM).



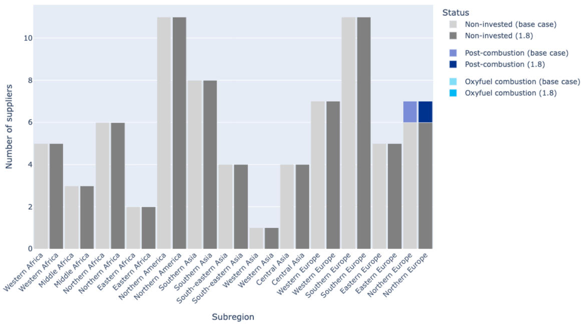
(b) Transportation cost factor 0.8 (no CBAM).



(c) Transportation cost factor 1.2 (no CBAM).

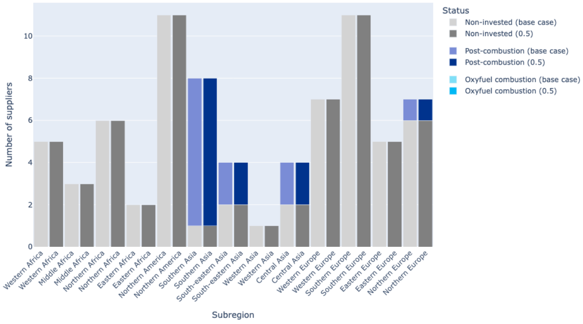


(d) Transportation cost factor 1.5 (no CBAM).

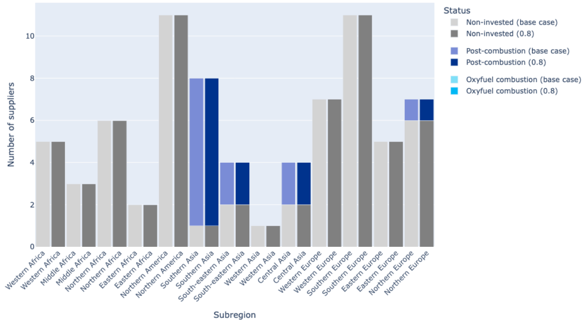


(e) Transportation cost factor 1.8 (no CBAM).

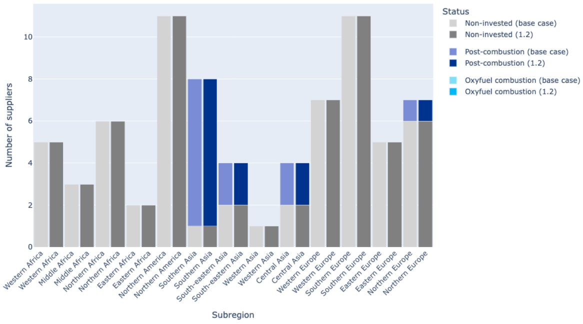
Figure H.8: Investment decisions by subregion under varying transportation-cost factors, compared to the base case, when CBAM is not applied.



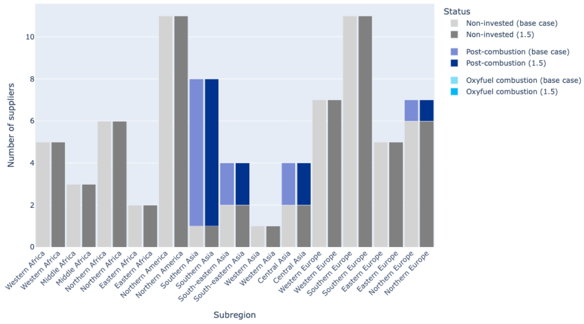
(a) Transportation cost factor 0.5 (with CBAM).



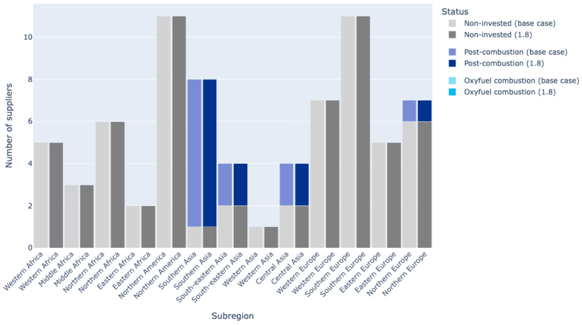
(b) Transportation cost factor 0.8 (with CBAM).



(c) Transportation cost factor 1.2 (with CBAM).



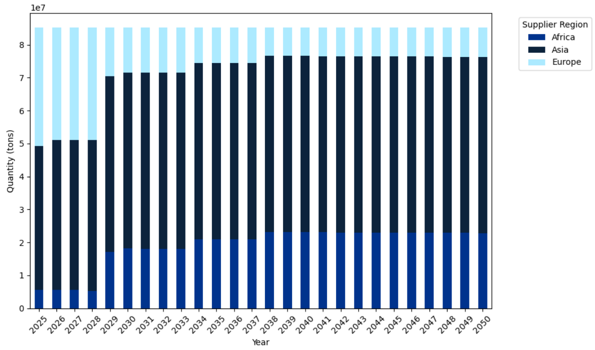
(d) Transportation cost factor 1.5 (with CBAM).



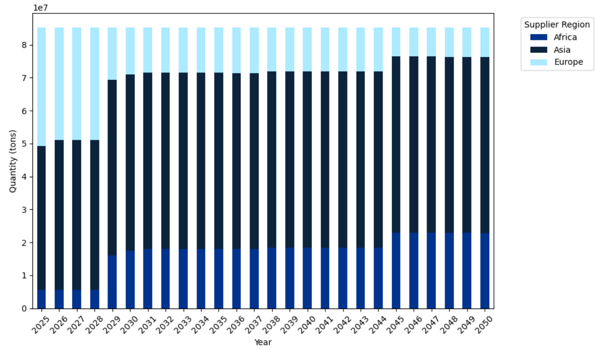
(e) Transportation cost factor 1.8 (with CBAM).

Figure H.9: Investment decisions by subregion under varying transportation-cost factors, compared to the base case, when CBAM is applied.

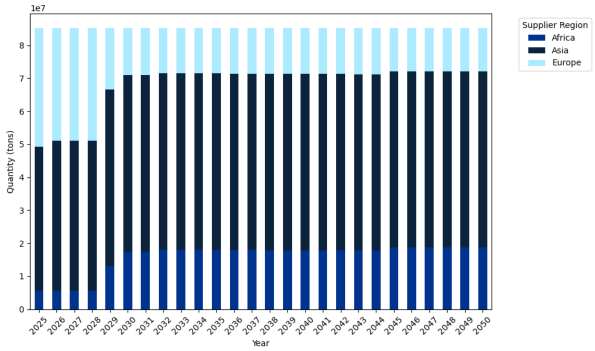
Distribution Shares



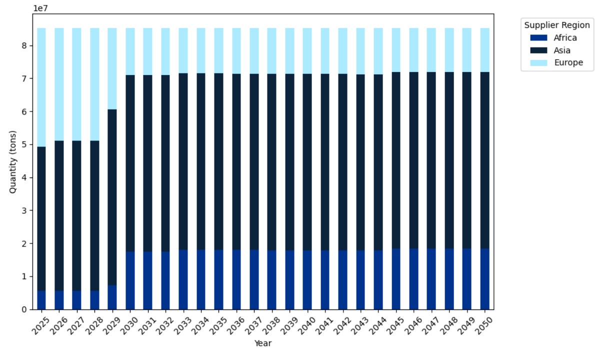
(a) Transportation cost factor 0.5 (no CBAM).



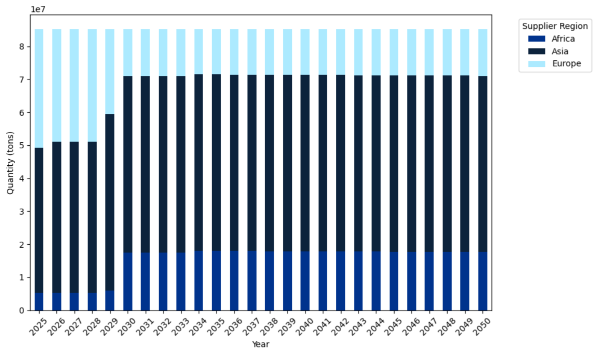
(b) Transportation cost factor 0.8 (no CBAM).



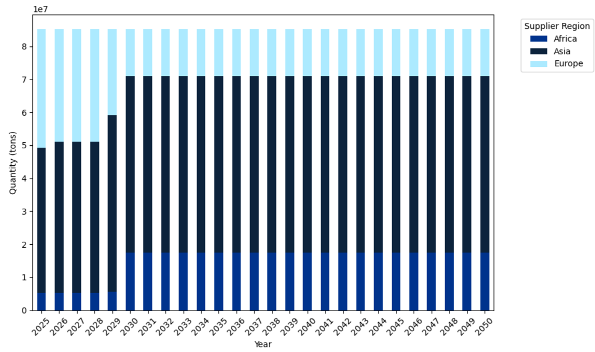
(c) Transportation cost factor 1 (no CBAM).



(d) Transportation cost factor 1.2 (no CBAM).

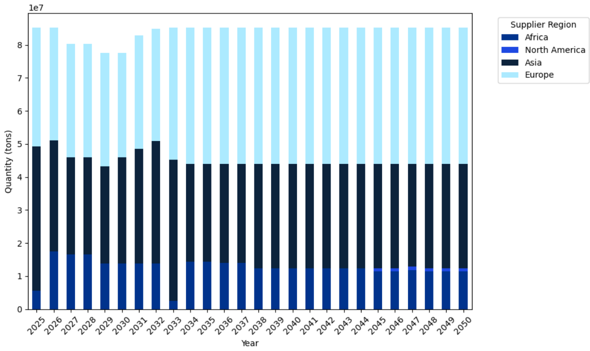


(e) Transportation cost factor 1.5 (no CBAM).

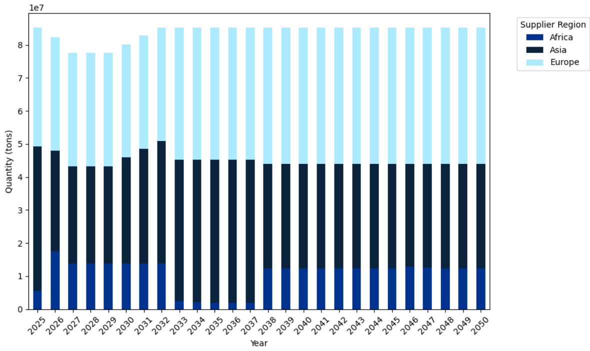


(f) Transportation cost factor 1.8 (no CBAM).

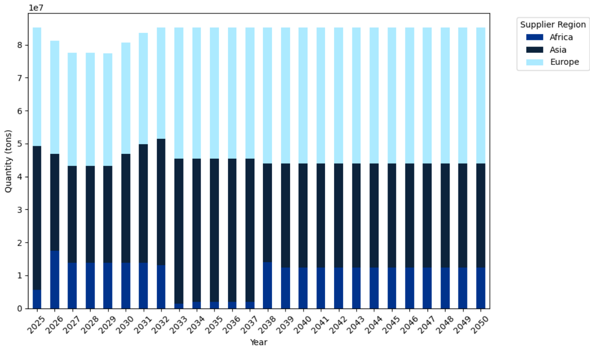
Figure H.10: Cement supply shares to Europe over time under varying transportation-cost factors, when CBAM is not applied.



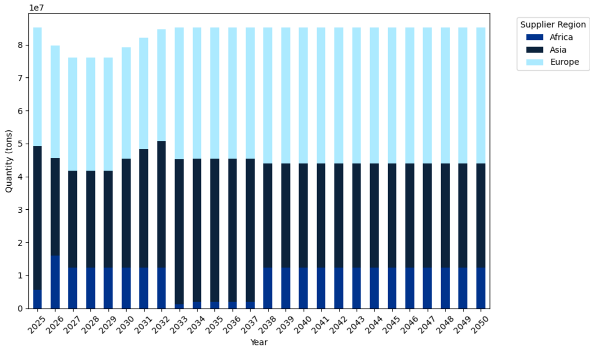
(a) Transportation cost factor 0.5 (with CBAM).



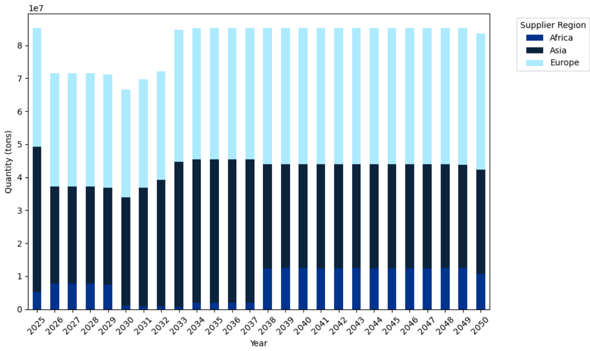
(b) Transportation cost factor 0.8 (with CBAM).



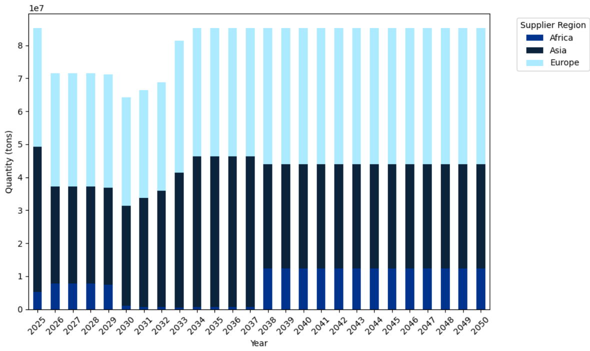
(c) Transportation cost factor 1 (with CBAM).



(d) Transportation cost factor 1.2 (with CBAM).



(e) Transportation cost factor 1.5 (with CBAM).

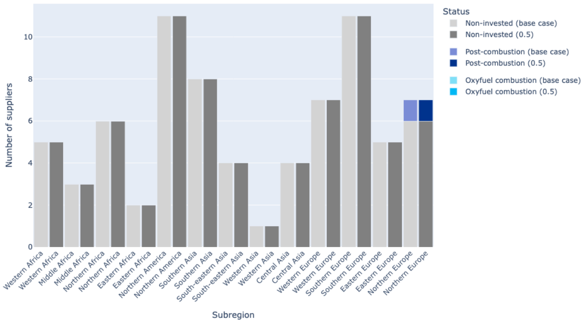


(f) Transportation cost factor 1.8 (with CBAM).

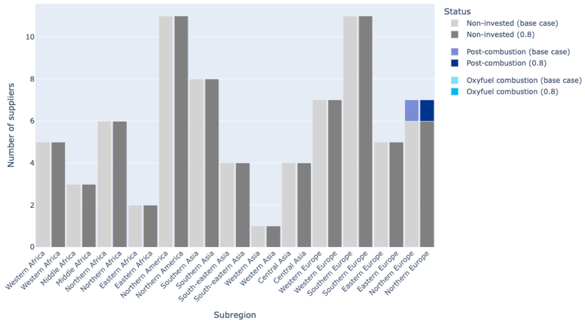
Figure H.11: Cement supply shares to Europe over time under varying transportation-cost factors, when CBAM is applied.

H.4.3 Transport and Storage Costs

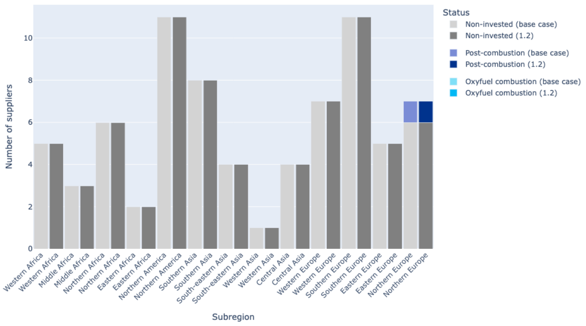
Investment Decisions



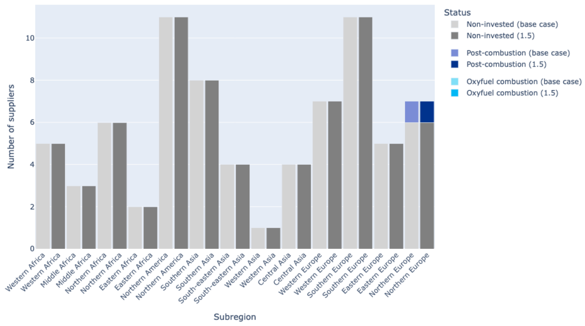
(a) Transport and storage cost factor 0.5 (no CBAM).



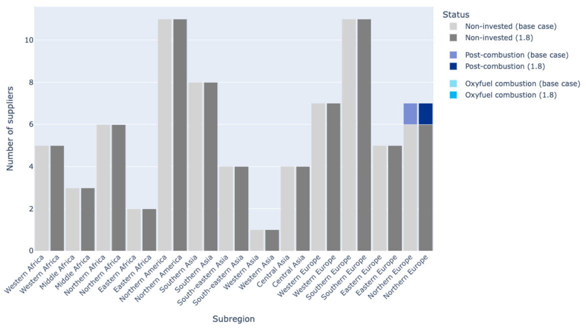
(b) Transport and storage cost factor 0.8 (no CBAM).



(c) Transport and storage cost factor 1.2 (no CBAM).

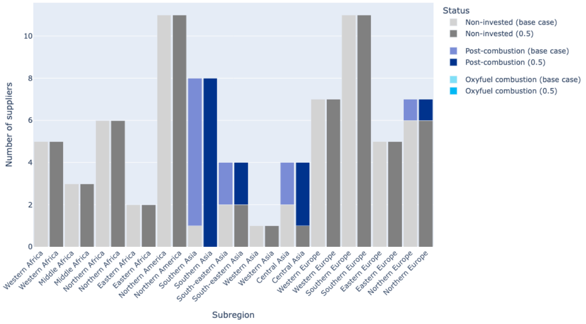


(d) Transport and storage cost factor 1.5 (no CBAM).

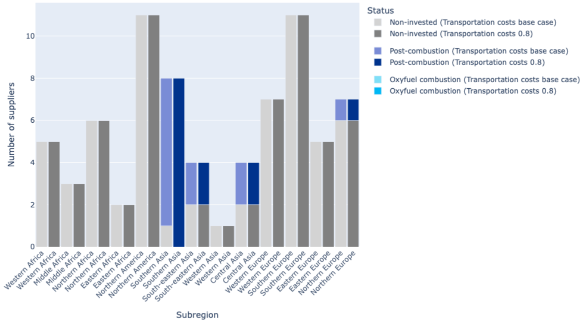


(e) Transport and storage cost factor 1.8 (no CBAM).

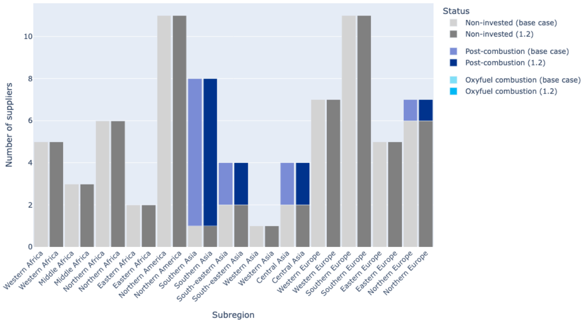
Figure H.12: Investment decisions by subregion under varying transport storage costs, compared to the base case, when CBAM is not applied.



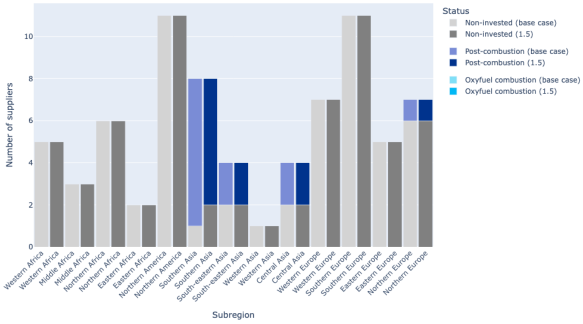
(a) Transport and storage cost factor 0.5 (with CBAM).



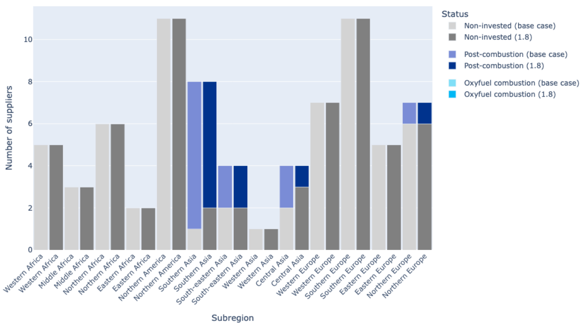
(b) Transport and storage cost factor 0.8 (with CBAM).



(c) Transport and storage cost factor 1.2 (with CBAM).



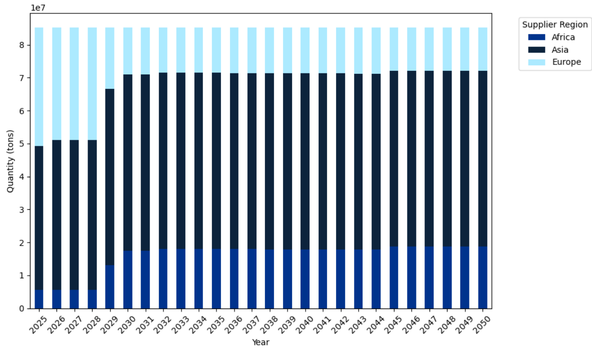
(d) Transport and storage cost factor 1.5 (with CBAM).



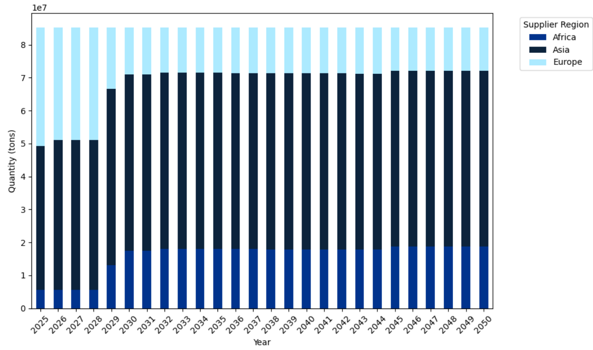
(e) Transport and storage cost factor 1.8 (with CBAM).

Figure H.13: Investment decisions by subregion under varying transport storage costs, compared to the base case, when CBAM is applied.

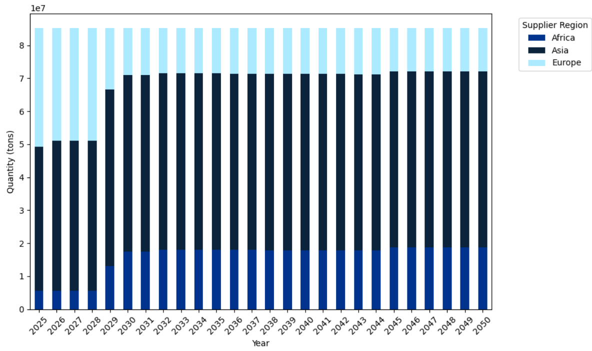
Distribution Shares



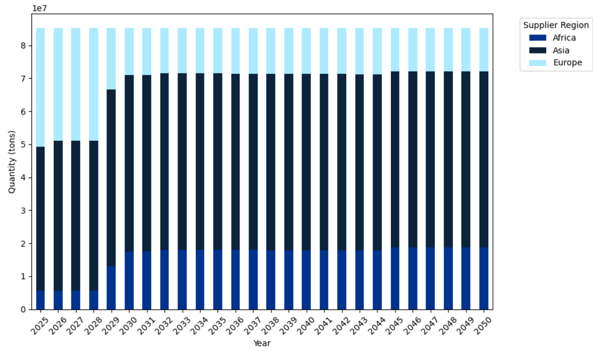
(a) Transport and storage cost factor 0.5 (no CBAM).



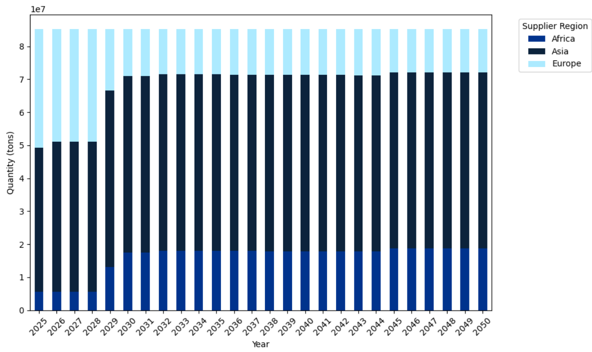
(b) Transport and storage cost factor 0.8 (no CBAM).



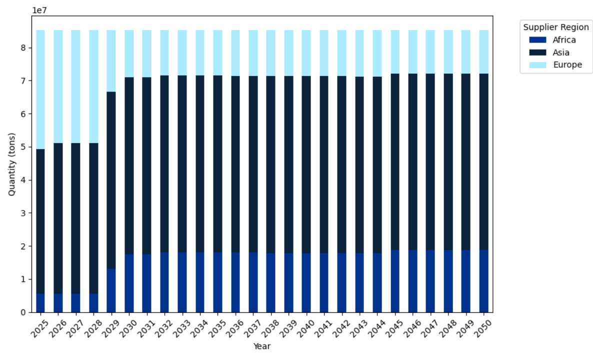
(c) Transport and storage cost factor 1 (no CBAM).



(d) Transport and storage cost factor 1.2 (no CBAM).

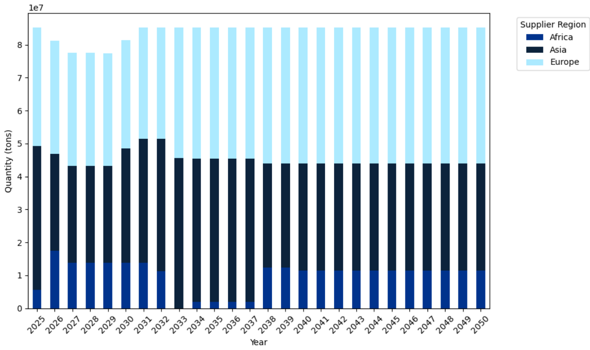


(e) Transport and storage cost factor 1.5 (no CBAM)..

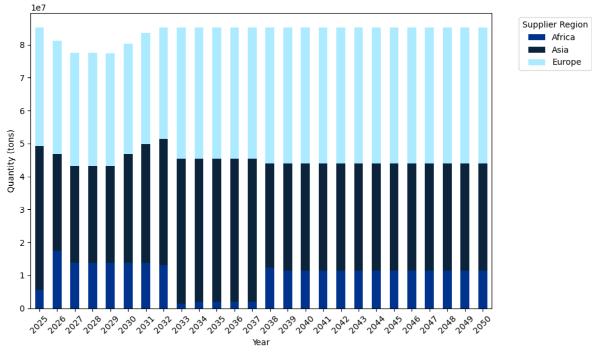


(f) Transport and storage cost factor 1.8 (no CBAM).

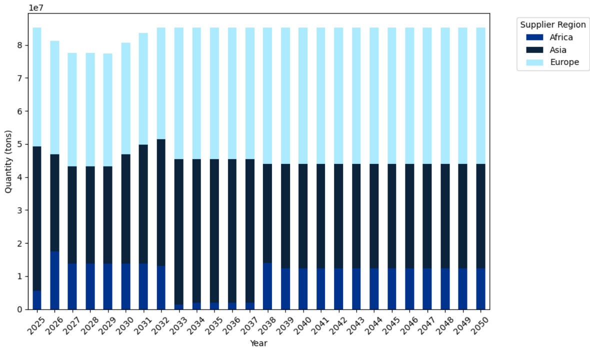
Figure H.14: Cement supply shares to Europe over time under varying transport and storage cost factors, when CBAM is not applied.



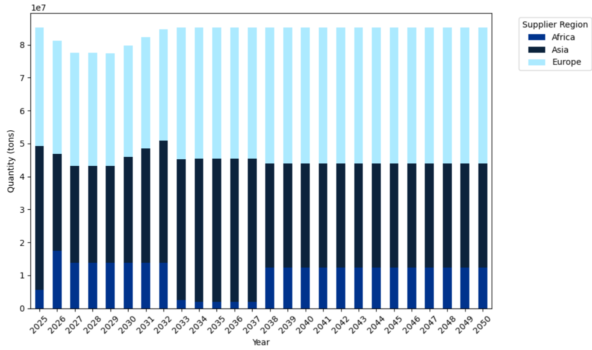
(a) Transport and storage cost factor 0.5 (with CBAM).



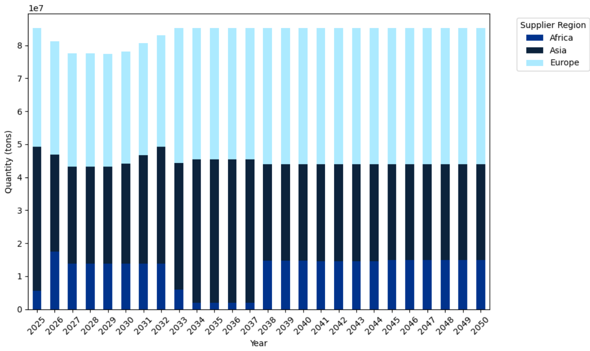
(b) Transport and storage cost factor 0.8 (with CBAM).



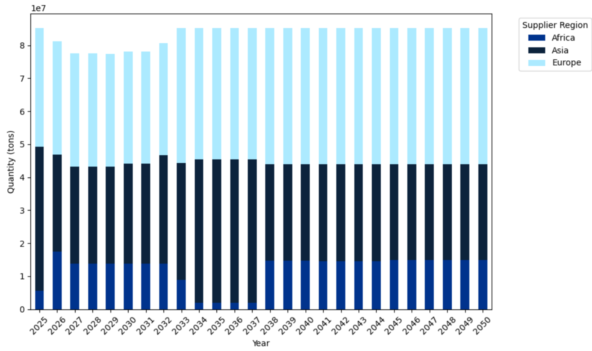
(c) Transport and storage cost factor 1 (with CBAM).



(d) Transport and storage cost factor 1.2 (with CBAM).



(e) Transport and storage cost factor 1.5 (with CBAM).

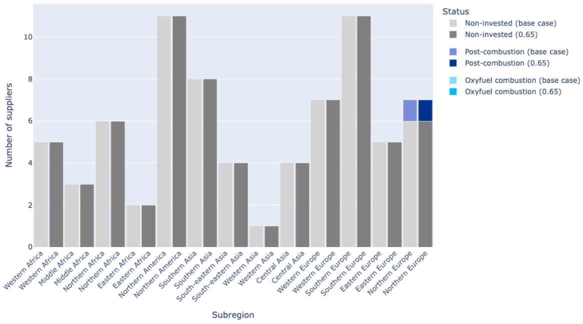


(f) Transport and storage cost factor 1.8 (with CBAM).

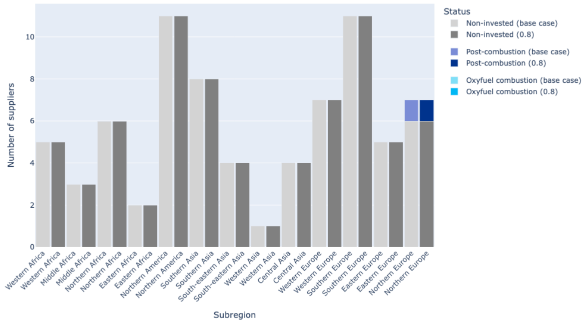
Figure H.15: Cement supply shares to Europe over time under varying transport and storage cost factors, when CBAM is applied.

H.4.4 Investment Costs

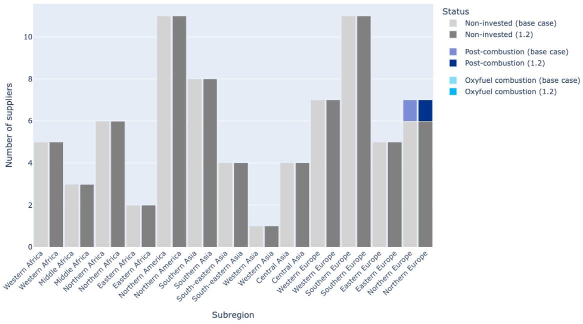
Investment Decisions



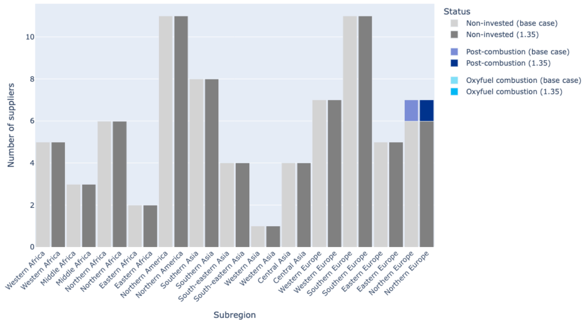
(a) Investments cost factor 0.65 (no CBAM).



(b) Investments cost factor 0.8 (no CBAM).

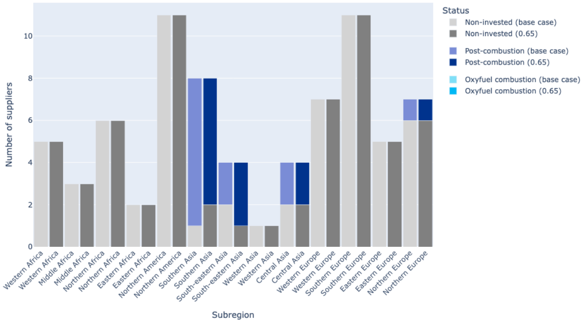


(c) Investments cost factor 1.2 (no CBAM).

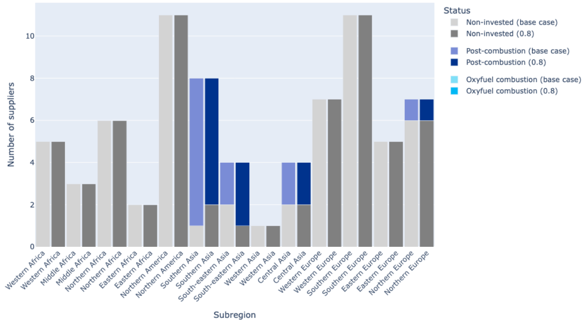


(d) Investments cost factor 1.35 (no CBAM).

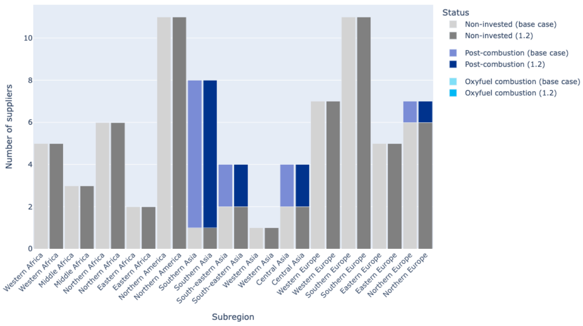
Figure H.16: Regional carbon capture investment shares under varying capital-cost factors, compared to the base case, when CBAM is not applied.



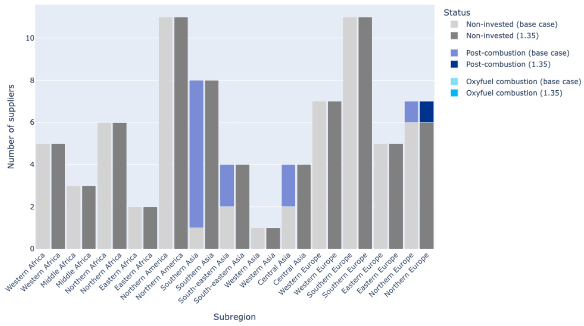
(a) Investments cost factor 0.65 (with CBAM).



(b) Investments cost factor 0.8 (with CBAM).



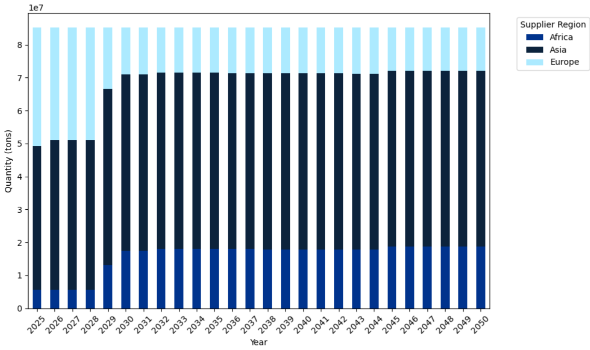
(c) Investments cost factor 1.2 (with CBAM).



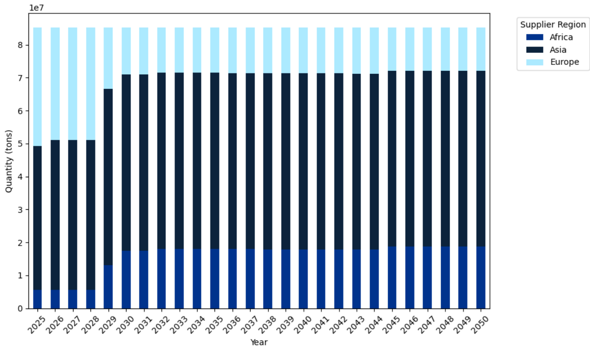
(d) Investments cost factor 1.35 (with CBAM).

Figure H.17: Regional carbon-capture investment shares under varying capital-cost factors, compared to the base case, when CBAM is applied.

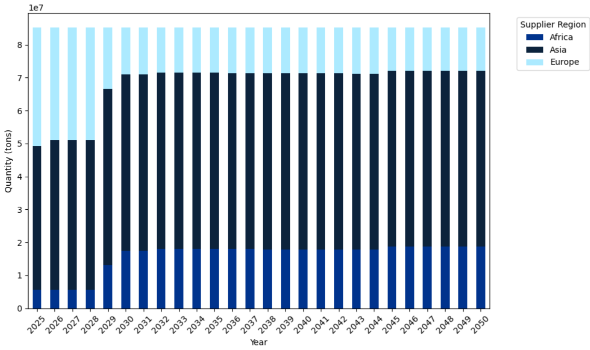
Distribution Shares



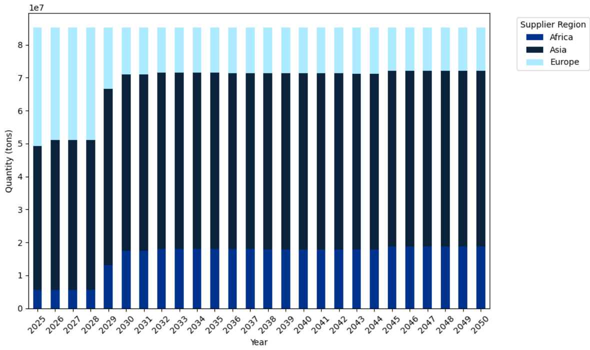
(a) investment costs 0.65 (w/o CBAM).



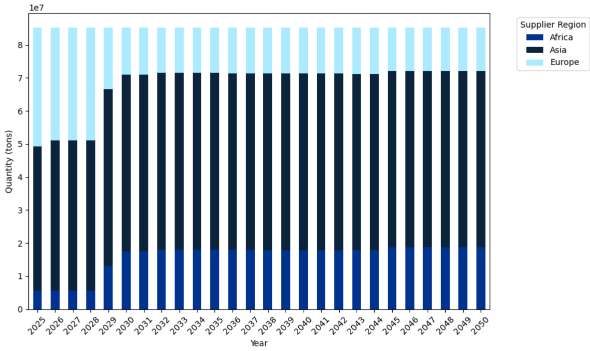
(b) investment costs 0.8 (w/o CBAM).



(c) investment costs 1 (w/o CBAM).

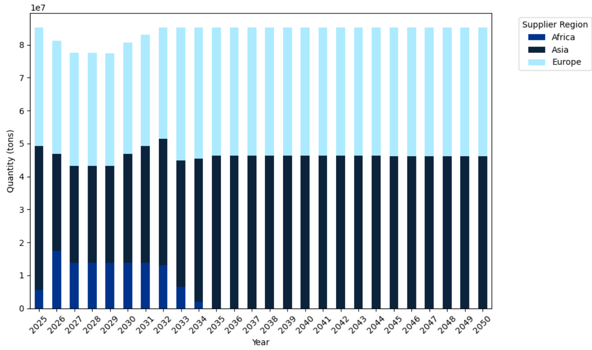


(d) investment costs 1.2 (w/o CBAM).

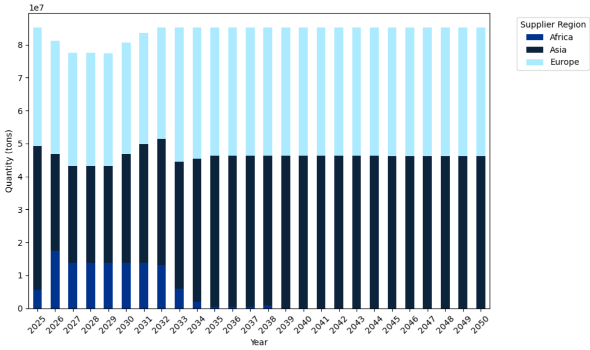


(e) investment costs 1.35 (w/o CBAM).

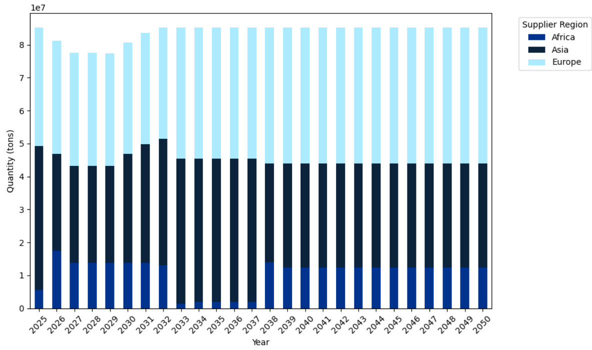
Figure H.18: Cement distribution towards Europe in absence of the CBAM regulation.



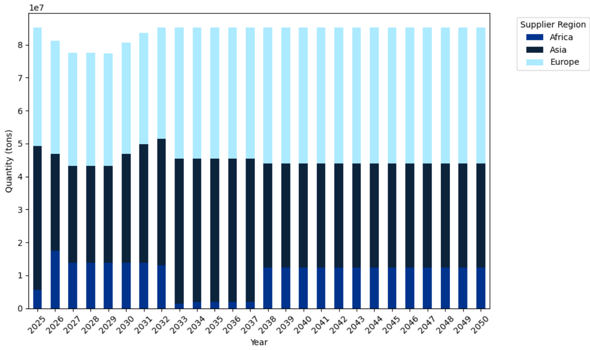
(a) xxx



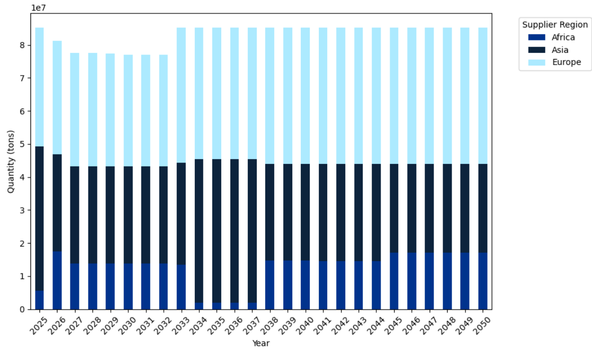
(b) xxx



(c) xxx



(d) xxx



(e) xxx

Figure H.19: Cement distribution towards Europe under the CBAM regulation.

Appendix I

Scientific Paper

Optimising Cement Supply Chain Investment and Distribution Decisions Under The CBAM: An Integrated MILP Decision Framework

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Contact: rlkarthaus@tudelft.nl (Robin Karthaus)

Abstract
This paper presents an integrated optimisation framework for decarbonisation technology investments and distribution decision-making in the cement industry under evolving carbon regulations. Focusing on carbon capture technology investment and cement distribution, the study examines the impact of the European Union's Carbon Border Adjustment Mechanism (CBAM). Using a Mixed-Integer Linear Programming (MILP) approach, the model simultaneously determines optimal locations for carbon capture technology investments and allocates global cement flows across global markets. A case study on Heidelberg Materials evaluates the model under three International Energy Agency scenarios – Stated Policies (STEPS) scenario, the Announced Pledges (APS) scenario, and the Net Zero Emissions (NZE) scenario – with and without the CBAM. The results show that the CBAM has a significant influence on investment patterns, often shifting retrofit viability from high-cost regions, such as Europe, to lower-cost regions abroad. Additionally, under both conservative and aggressive policy pathways (STEPS and NZE), the CBAM contributes to a reconfiguration of trade flows that favours European domestic production. Sensitivity analyses underscore production costs as the most significant determinant affecting the economic viability of carbon capture investments. The findings demonstrate how policy instruments, such as the CBAM, reshape global supply chains and underscore the importance of integrated decision-support tools for the cement industry in navigating through regulatory uncertainty. This research offers practical insights for industry stakeholders and policymakers, as well as a decision-support tool that can be used to align profitability with climate objectives in hard-to-abate sectors.
Keywords: Carbon Capture, Cement Industry, CBAM, MILP, Carbon Pricing, Supply Chain Optimisation

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Highlights

- Integrates strategic investments in carbon capture technologies with cement distribution decisions using a MILP optimisation model;
- Models cement flows under carbon pricing mechanisms using IEA price scenarios;
- Identifies shifts in carbon capture investments from high-cost regions to low-cost regions due to the introduction of the CBAM;
- Quantifies policy impact on Europe's cement trade;
- Provides a decision-support framework for navigating regulatory shifts.

1 Introduction

The cement industry is crucial to global economic development, underpinning infrastructure expansion, urbanisation, and overall growth. As the second most consumed material globally, after water, cement production significantly contributes to human development (Goggins, 2024). However, it is also responsible for substantial environmental impacts, accounting for approximately 6–8% of global carbon emissions, primarily resulting from the calcination process and fuel combustion during clinker production (Cadavid-Giraldo et al., 2020; Ige et al., 2024; Wang and Papadokonstantakis, 2024). With global cement production increasing from approximately 200 million tonnes annually in 1950 to over 4 billion tonnes today, primarily driven by growth in developing economies (Head et al., 2021), addressing the industry's environmental footprint has become a pressing challenge.

Given the inherently difficult-to-abate nature of carbon emissions in the cement industry, carbon capture technologies are vital for meeting decarbonisation targets – alternative cement chemistries and efficiency improvements alone cannot deliver the required reductions within the necessary timeframe (Cormos, 2022; Li et al., 2013; Hills et al., 2016). Technologies such as post-combustion capture, oxy-fuel combustion, and direct separation offer pathways to substantial emissions reductions (Bosoaga et al., 2009; Gerbelová et al., 2017). Despite their potential, widespread adoption remains hindered by high capital and operational costs, as well as uncertainties surrounding regulatory frameworks.

Adding complexity to this landscape is the evolving policy environment. Notably, the European Union (EU) has introduced the Carbon Border Adjustment Mechanism (CBAM), designed to impose a carbon price on imported goods equivalent to that paid by domestic producers under the EU Emissions Trading System (EU ETS) European Commission, 2024. This mechanism aims to prevent carbon leakage – a phenomenon where emissions-intensive production shifts to regions with less stringent regulations (European Commission, nd) – thus maintaining competitive fairness and environmental integrity (Hayes et al., 2024). The transitional phase of the CBAM commenced in 2023, with full implementation scheduled for 2026, which is expected to significantly impact global supply chains, particularly for internationally traded commodities such as cement.

Globally, carbon pricing mechanisms are gaining momentum, with 80 jurisdictions implementing or planning schemes to incentivise emissions reductions and reshape industrial competitiveness (World Bank, 2025). Nevertheless, despite the mounting pressure to decarbonise, the cement industry's strategic responses remain fragmented and uncertain. Producers face complex trade-offs between investing in costly carbon capture technologies and adjusting distribution flows to minimise carbon costs under emerging policies, such as the CBAM. Without an integrated framework, the cement industry is likely to delay or avoid adopting these expensive investments, and policymakers will struggle to anticipate or evaluate the effects of new carbon pricing policies. This uncertainty highlights a critical gap: there is currently no comprehensive tool to help cement companies and policymakers understand how carbon pricing mechanisms interact with supply chain operations, informing optimal investment and distribution decisions.

To address this need, this paper presents a comprehensive decision-support framework based on a Mixed-Integer Linear Programming (MILP) model that jointly optimises strategic investments in carbon capture technologies and cement distribution flows under various carbon pricing scenarios. The model explicitly incorporates CBAM-related costs and carbon pricing uncertainties to assess their impacts on supply chain configurations. By integrating both decision types, the framework supports robust decision-making for cement producers, enabling them to identify cost-effective pathways to reduce emissions while also providing policymakers with insights into how regulatory measures influence industry behaviour. This dual perspective ensures that both industry stakeholders and regulators can better anticipate, evaluate, and plan for the challenges of decarbonising one of the world's carbon-intensive industries.

The remainder of this paper is structured as follows: section 2 reviews relevant literature, highlighting existing research gaps; section 3 outlines the integrated problem context addressed in this study; section 4 presents the methodology and details the formulation of the MILP model; section 5 discusses the results of the scenario and sensitivity analyses, based on a case study involving Heidelberg Materials; section 6 summarises the key findings, outlines implications for industry and policymakers, and proposes directions for future research.

2 Literature review

This section reviews the academic and policy literature relevant to the decarbonisation of the cement industry, focusing on three main themes: carbon pricing mechanisms, supply chain optimisation, and carbon capture technologies.

The EU ETS has been the central mechanism for regulating industrial greenhouse gas emissions, of which the cement sector is a key contributor. It operates as a cap-and-trade system, allocating a finite number of allowances to emit carbon, which firms can trade among themselves (European Commission, 2023b). While the EU ETS has gradually strengthened through reduced cap levels and allowance phaseouts, it has been criticised for fostering carbon leakage – a phenomenon whereby emissions-intensive production shifts to jurisdictions with laxer climate regulations to avoid compliance costs European Commission (nd); Hayes et al. (2024).

In response, the EU developed the CBAM, which aims to impose a carbon levy on imported goods equivalent to what domestic producers pay under the EU ETS European Commission (2024). By equalising the carbon cost burden between EU and non-EU producers, the CBAM seeks to protect the competitiveness of European industry and create incentives for global decarbonisation. The mechanism entered its transitional phase in 2023 and is scheduled for full implementation in 2026. During the transitional phase, embedded emissions in imported goods must be reported but are not yet subject to financial penalties. This staged implementation has broad implications for globally traded materials, such as cement, and requires producers to reassess both their investment strategies and global distribution patterns.

The CBAM initially covers a limited number of sectors, including cement, iron, steel, aluminium, and fertilisers, but its scope may expand. The cement sector, in particular, is vulnerable due to the high emissions intensity of clinker production. Consequently, the evolving carbon pricing regime adds complexity to supply chain decisions by introducing new cost structures based on the location of production.

The adoption of carbon capture technologies represents a substantial financial commitment, with capital requirements that can exceed several hundred million euros per plant. Production costs for cement vary widely across major global regions – for example, between Europe and Asia (Cook, 2009; Barker et al., 2008) – creating significant disparities in the economic attractiveness of decarbonisation investments. Despite the financial and environmental importance of these differences, existing models fail to capture the whole interplay between investment in carbon-reducing technologies and distribution decisions.

While several mitigation pathways exist, multiple sources emphasise that reaching deep decarbonisation targets in the cement industry will not be feasible without investments in carbon capture technologies (Hills et al., 2016; Biniek et al., 2024). Alternative levers such as energy efficiency improvements and clinker substitution may contribute, but alone, they are insufficient to address the scale and urgency of emissions reduction required (Cormos, 2022; Li et al., 2013). Consequently, this study reviews post-combustion, oxy-fuel, and direct separation technologies as the most promising retrofit options for existing cement infrastructure.

Post-combustion capture is the most mature technology and is considered the most retrofit-friendly among carbon capture technologies. It typically involves chemical absorption to extract carbon from flue gases (Bosoaga et al., 2009). Its primary advantage lies in allowing complete retrofitting without fundamentally altering the production line (Li et al., 2013; Hills et al., 2016). There already exists one full-scale operational production plant in Norway, operated by Heidelberg Materials (Brevik CCS Project, 2025). The retrofit can be completed within a one-month annual shutdown period (Hills et al., 2016), allowing the installation to be scheduled without disrupting regular production operations.

Oxy-fuel combustion involves burning fuel in pure oxygen instead of air, resulting in a flue gas composed mainly of carbon and water vapour, which simplifies carbon capture (Cormos, 2022). However, complete oxy-fuel systems are not currently retrofit-friendly due to the need for extensive kiln modifications and auxiliary equipment (Gerbelová et al., 2017). Partial oxy-fuel systems offer a more practical interim solution (Hills et al., 2016). Although described as "relatively easy" compared to complete oxy-fuel retrofits, the retrofit still requires replacing major components such as the precalciner and preheater. Following Hills et al. (2016), this study assumes a retrofit duration of approximately one year to reflect the intermediate installation complexity of the technology, with the earliest feasible retrofit assumed to occur in 2030.

Direct separation targets carbon emissions released during the calcination process. It relies on an indirectly heated calciner that isolates pure carbon streams, allowing for efficient capture without the dilution seen in flue gas (Driver et al., 2022). Although the technology shows promise in terms of energy efficiency and carbon purity, it is not included in the optimisation model due to insufficient publicly available data to represent it reliably.

Existing optimisation methods in the cement sector typically address only a single layer of decision-making or do not incorporate the interconnection with carbon pricing mechanisms, limiting their ability to capture the complex trade-offs required for strategic decarbonisation. For instance, Wang and Papadokonstantakis (2024) developed a stochastic multi-period optimisation model for carbon capture investments; however, their analysis is confined to a single-country setting and does not incorporate cross-border distribution dynamics or the implications of policies such as the CBAM. Similarly, Bakhtavar et al. (2019) introduced a multi-objective optimisation framework for locating new cement plants, balancing cost and environmental performance; nonetheless, their model also omits carbon pricing mechanisms. Meanwhile, Mokhtar and Nasooti (2020) presented a plant-level decision support tool focused solely on improving operational efficiency through energy management, lacking any integration of strategic investment or distribution considerations.

In reviewing alternative modelling paradigms, System-Dynamic simulation models were found to be effective for capturing feedback loops and long-term dynamics in the cement industry. Regardless, they cannot optimise discrete investment choices or distribution flows (Ige et al., 2024; Kunche and Mielczarek, 2021). Life-Cycle Assessment provides detailed environmental impact analysis but cannot identify optimal decisions or investment timing (Müller et al., 2020). Agent-based modelling can simulate heterogeneous investor behaviour but does not guarantee globally optimal solutions (Sachs et al., 2019). At the same time, Multi-Criteria Decision-Making frameworks rank alternatives based on qualitative and quantitative criteria but do not solve integrated optimisation problems (Mokhtar and Nasooti, 2020).

By contrast, MILP offers a unique advantage for this research: it can simultaneously model binary investment decisions and continuous distribution flows within a unified optimisation framework, directly reflecting the intertwined decisions required under carbon pricing mechanisms. Although MILP imposes linearity, key cost components – including production, transportation, and carbon costs – can be approximated as linear over the planning horizon, ensuring model accuracy without undue computational complexity. Therefore, MILP was selected as the most suitable methodology, as its strengths closely align with the research objective of optimising both investment and distribution strategies under dynamic policy scenarios. At the same time, its limitations do not materially affect the key outcomes of this analysis.

This study makes two primary contributions to the literature. First, it develops a novel MILP optimisation model that integrates strategic investment in carbon capture technologies with operational cement distribution under regulatory uncertainty. Second, it incorporates dynamic carbon pricing trajectories and trade-related policies, such as the CBAM, into the decision-making process, providing a holistic framework for decarbonisation planning in global cement supply chains. This addresses a clear gap in current research, where investment and operational decisions are too often analysed in isolation. By explicitly incorporating retrofit feasibility, emissions costs, and distribution logistics, the model provides a more realistic and policy-responsive tool for industry planning and academic analysis.

3 Problem description

The cement industry is under significant pressure to reduce carbon emissions due to its substantial environmental footprint and evolving international climate policies. Among these policies, the EU's CBAM introduces complexity by imposing costs based on the embedded carbon emissions in imported goods. This regulation reshapes global market dynamics and presents new challenges for cement producers, who must align long-term investments in carbon-reducing technologies with their global distribution strategies. By capturing the interplay between these decisions, the model not only supports profit-maximising investment choices but also reveals how distribution patterns are shaped by these decisions and regulatory mechanisms, such as the CBAM, offering both economic and political insights.

The CBAM seeks to prevent carbon leakage by equalising the cost burden of emissions between domestic and foreign producers, thereby significantly impacting operational and investment strategies within global cement supply chains. However, existing optimisation frameworks inadequately capture these complex interactions. Cement producers require an integrated decision-support framework capable of concurrently optimising investments in carbon capture technologies and distribution decisions to respond effectively to regulatory changes and market uncertainties. The central problem is thus defined as the absence of an integrated decision-making framework capable of concurrently optimising strategic investments in carbon-reducing technologies and distribution logistics, especially under evolving regulatory conditions typified by CBAM.

This research addresses this specific problem by developing and applying a MILP model that integrates both decision-making layers. The model explicitly incorporates investments in carbon capture technologies and global cement distribution logistics under varying regulatory scenarios. By doing so, it aims to determine optimal configurations that maximise profitability, accounting comprehensively for production, investment, transportation, storage, and regulatory compliance costs. Through this integrated approach, the model provides essential support for decision-making, enabling cement producers to strategically and operationally adapt to regulatory pressures and market uncertainties.

4 Methodology

The methodology employed in this study is centred around the development and application of a MILP model. MILP is particularly suited for problems involving binary and continuous variables. In the case of this study, the investment decision will be modelled as a binary (yes or no) decision. In contrast, the distribution of cement will be modelled as a continuous decision. This methodology integrates various input parameters such as production capacities, transport costs, emission intensities, and carbon pricing mechanisms into a comprehensive optimisation framework. Scenario and sensitivity analyses are further utilised to examine the robustness of model outcomes under varying market and regulatory conditions, thereby providing a practical decision-support tool for the cement industry.

4.1 Data collection

The data used in this analysis is primarily sourced from the *Global Cement Assets Database*, which provides detailed information on the locations, capacities, and ownership of cement plants (Global Cement and Concrete Association, 2025). Trade data on cement at the country level was obtained from the *BACI Bilateral Trade Flows Database* (Gaulier and Zignago, 2025). By combining these two datasets, historical cement demand was estimated and subsequently used to forecast future demand.

Default values for embedded carbon emissions in cement production were gathered from official sources, with all plants assumed to exhibit uniform emission intensities (European Commission, 2023a). Transportation costs were derived from *UNCTAD's Transport Costs* dataset (United Nations Conference on Trade and Development, 2024), while references including IEA

(2025), Roussanaly et al. (2021), Myers et al. (2024), and Smith et al. (2021) were employed to estimate transport and storage costs associated with carbon capture and storage logistics.

Additionally, EBITDA values for estimating potential revenues were compiled from multiple sources (World Economic Forum, 2023; top, 2025; Panichi et al., 2022), with these figures multiplied by the estimated production costs per ton of cement. Various techno-economic reports specific to carbon capture technologies were also consulted (Hills et al., 2016; Røsjorde and Carpenter, nd; Cook, 2009; Barker et al., 2008; Gerbelová et al., 2017; Hegerland et al., 2006).

For a comprehensive discussion of data collection, processing methods, and the assumptions underlying the model, refer to Chapter 4 of Karthaus (2025).

4.2 Notation

Here, the key components of the model are defined. The sets specify the structural elements of the model, including production facilities, demand nodes, and carbon capture technologies. Parameters provide fixed input data that guide decision-making, such as production capacities, carbon prices, and emission factors, some of which vary over time. Decision variables represent the choices made in the model, capturing both investment and distribution decisions.

Subscripts indicate the dimensions of the decision space: i refers to individual production facilities (set F), j to demand nodes (set D), t to discrete time periods over the 2025–2050 planning horizon (set T), and e to technology alternatives (set E), specifically baseline (B), post-combustion (P), or oxy-fuel (O) technologies.

Model parameters fall into four categories: capacity and timing parameters (cap_i, μ_e), defining annual throughput and retrofit lead times; cost parameters (ρ_{ie}, τ_{ij}, ψ_{iet}, σ_{ijet}, ζ_{ie}, λ_e), encompassing production, transport, emissions, CBAM levies, storage, and investment costs; market and demand parameters (q_{jt}, Q_{tot}, β_c, δ_j), specifying customer requirements and market constraints; and revenue parameters (π_{jt}), representing unit selling prices at demand nodes.

The notations for the different sets, parameters, and decision variables used to construct the model, along with their descriptions, domains, and units, are provided in Table 1.

4.3 Problem formulation

The optimisation model in this study determines the optimal investment and distribution strategy for cement suppliers, aiming to maximise profit while complying with technical, economic, and policy-driven constraints. The mathematical model is formulated as follows:

Table 1: Definition of sets, parameters, and decision variables used in the optimisation model.

Symbol	Parameter	Domain	Unit
Sets and indices			
F	Set of cement production facility nodes	$i \in F$	
D	Set of demand nodes	$j \in D$	
T	Planning horizon ($T = \{T^{Min}, ..., T^{Max}\}$)[a]	$t \in T$	
E	Set of carbon capture technologies and baseline option ($E = \{\mathrm{B}, \mathrm{P}, \mathrm{O}\}$)[b]	$e \in E$	
Parameters			
β_c	Maximum historical share of total cement shipments to region c	$0 \leq \beta_c \leq 1$	[fraction]
Θ	Maximum annual investment budget	$\Theta \in \mathbb{R}^+$	[$/year]
cap_i	The yearly production capacity available ($\mathrm{cap}_i = C_{\mathrm{B}i} + C_{\mathrm{P}i} + C_{\mathrm{O}i}$)	$\mathrm{cap}_i \in \mathbb{R}^+$	[ton]
$\mathrm{Q}_{\mathrm{tot}}$	Total annual production capacity of all the production facilities	$\mathrm{Q}_{\mathrm{tot}} \in \mathbb{R}^+$	[tons/year]
μ_e	Time needed for retrofit the production facility	$\mu_e \in \mathbb{N}^+$	[years]
τ_{ij}	Transportation cost per ton cement	$\tau_{ij} \in \mathbb{R}^+$	[$/ton]
ρ_{ie}	Production costs for one ton cement	$\rho_{ie} \in \mathbb{R}^+$	[$/ton]
ψ_{iet}	Cost of emissions from facility's region per ton cement	$\psi_{iet} \in \mathbb{R}^+$	[$/ton]
σ_{ijet}	Net CBAM charge per ton of cement	$\sigma_{ijet} \in \mathbb{R}^+$	[$/ton]
ζ_{ie}	Transport and storage cost per ton cement	$\zeta_{ie} \in \mathbb{R}^+$	[$/ton]
λ_e	Capital cost of investment	$\lambda_e \in \mathbb{R}^+$	[$]
δ_j	Whether paid carbon taxes in production region are deductible in the demand region	$\delta_j \in \{0,1\}$	[binary]
q_{jt}	Demand of the customer	$q_{jt} \in \mathbb{R}^+$	[tons/year]
π_{jt}	Revenue for 1 ton of cement at customer	$\pi_{jt} \in \mathbb{R}^+$	[$/ton]
Variables			
x_{ijte}	Amount of cement distributed	$x_{ijte} \in \mathbb{R}^+$	[ton]
y_{iet}	Indicates the active technology	$y_{iet} \in \{0,1\}$	[binary]

[a] The model considers a 25-year planning horizon starting in 2025, such that $T^{\mathrm{Min}} = 2025$ and $T^{\mathrm{Max}} = 2050$.
[b] The elements of set E represent the following investment options: B — baseline case without carbon capture; P — investment in post-combustion carbon capture; O — investment in oxy-fuel combustion carbon capture.

$$\max \quad \sum_{i\in F}\sum_{j\in D}\sum_{t\in T}\sum_{e\in E}(\pi_{jt}-\rho_{ie}-\psi_{iet}-\sigma_{ijet}-\tau_{ij}-\zeta_{ie})\,x_{ijte} \;-\; \sum_{i\in F}\sum_{e\in E}\lambda_{ie}\,y_{ieT^{Max}} \tag{1}$$

$$\text{s.t.} \quad \sum_{j\in D} x_{ij2025,\mathrm{B}} \;\leq\; C_{\mathrm{B}i},\ \forall\, i\in F \tag{2}$$

$$\sum_{j\in D} x_{ij2025,\mathrm{P}} \;\leq\; C_{\mathrm{P}i},\ \forall\, i\in F \tag{3}$$

$$\sum_{j\in D} x_{ij,2025,\mathrm{O}} \;\leq\; C_{\mathrm{O}i},\ \forall\, i\in F \tag{4}$$

$$\sum_{j\in D} x_{ijte} \;\leq\; \mathrm{cap}_i\, y_{i,e,t} - \mathrm{cap}_i\,\mu_e(y_{iet}-y_{iet-1}) \tag{5}$$

$$\forall\, i \in F,\; e \in E,\; t \in T \setminus \{T^{Min}\}$$

$$\sum_{i\in F}\sum_{e\in E} x_{ijte} \;\le\; q_{jt},\; \forall\, j \in D,\; t \in T \tag{6}$$

$$y_{iet} - y_{ie,\,t+1} \;\le\; 0,\; \forall\, i \in F,\; e \in E \setminus \{\mathrm{B}\},\; t \in T \setminus \{T^{Max}\} \tag{7}$$

$$\sum_{e\in E} y_{iet} = 1,\; \forall\, i \in F,\; t \in T \tag{8}$$

$$y_{i\mathrm{O}t} = 0,\; \forall\, i \in F,\; t < 2030 \tag{9}$$

$$\sum_{e\in E}\sum_{i\in F}(y_{ie2026} - y_{ie2025})\lambda_e \;\le\; \Theta \tag{10}$$

$$\sum_{e\in E}\sum_{i\in F}(y_{iet+1} - y_{iet})\lambda_e \;\le\; \Theta,\; \forall t \in T \setminus \{T^{Max}\} \tag{11}$$

$$\sum_{i\in F}\sum_{j\in D_c}\sum_{e\in E} x_{ijte} \;\le\; \beta_c\, Q_{\mathrm{tot}},\; \forall\, c \in \mathcal{C},\; t \in T \tag{12}$$

where

$$\mathcal{C} = \{\text{Africa}, \text{Asia}, \text{Europe}, \text{North America}, \text{South America}, \text{Oceania}\},$$

$$D_c = \{\, j \in D \mid \text{continent}(j) = c\}.$$

The objective function (1) maximises total profit over the planning horizon by subtracting all cost components from total revenue. Revenue is earned by delivering cement to customer locations, calculated as the product of sales price π_{jt} and dispatched quantity x_{ijte}. From this revenue, the model deducts various cost terms: production costs ρ_{ie}, which depend on the facility and selected technology; emission-related costs ψ_{iet}, which vary by technology and time; CBAM-related carbon import costs σ_{ijet}; transportation costs τ_{ij}; and carbon transport and storage costs ζ_{ie}. Additionally, strategic investment costs λ_{ie} are subtracted at the end of the horizon for facilities that adopt a capture technology, captured by $y_{ieT^{Max}}$. Together, these components reflect the full range of operational, environmental, and strategic costs incurred throughout the cement supply chain.

Constraints (2)–(4) impose technology-specific production limits in the initial year (2025). They ensure that only cement volumes corresponding to existing baseline (B_i), post-combustion (P_i), or oxy-fuel combustion (O_i) capacity can be dispatched in that year. For example, since Heidelberg Materials operates only one post-combustion plant and no oxy-fuel units, P_i and O_i would reflect these initial availability levels.

Constraint (5) governs production capacity for all subsequent years. It ensures that for each supplier i, technology e, and year $t > 2025$, the total amount of cement dispatched does not exceed active capacity. The term y_{iet-1} indicates whether the technology was active in the previous period. If not, the right-hand side becomes zero, prohibiting production. The subtraction term accounts for retrofit downtime: when a facility transitions to a new technology e, a fraction μ_e of production is temporarily lost. For example, $\mu_{\mathrm{O}} = 1$ represents a full shutdown for oxy-fuel retrofitting, while $\mu_{\mathrm{B}} = \mu_{\mathrm{P}} = 0$ reflects no production loss for baseline and post-combustion upgrades.

Constraint (6) enforces that the amount of cement delivered to each customer j in each year

t cannot exceed their forecasted demand q_{jt}. This guarantees that the supply does not overshoot real market needs.

Constraint (7) ensures investment decisions are irreversible. Once a non-baseline technology e is adopted at facility i in year t, the same technology must remain active in year $t + 1$. This reflects the long-term commitment and physical permanence of technology investments.

Constraint (8) forces technology exclusivity: for every facility and year, exactly one technology option must be active – either the baseline or one of the carbon capture options. This avoids situations where multiple technologies operate simultaneously at the same facility.

Constraint (9) imposes a minimum adoption year for oxy-fuel combustion: it cannot be selected before 2030. This constraint aligns the model with findings from the literature, indicating the earliest plausible deployment timeline for this technology.

Constraints (10) and (11) implement annual investment budget limits. They sum new investment costs λ_e and restrict these to a fixed budget Θ for each year. For Heidelberg Materials, Θ is derived from reported capital expenditures in cement production for 2024, ensuring the model operates within realistic financial boundaries.

Constraint (12) prevents unrealistic allocation of cement flows to low-cost carbon markets. It limits the total amount of cement shipped to each continent c in each year t to a calibrated market share β_c times total global demand Q_{tot}. The β_c values are based on historical shipment shares observed between 2021 and 2024. By taking the maximum observed share per region, this constraint offers flexibility while avoiding unrealistic market concentration in carbon-favourable regions.

Together, these constraints and the objective function form a comprehensive optimisation framework that captures the strategic, operational, environmental, and policy dimensions of cement supply chain decisions under evolving climate regulations.

4.4 Scenario and Sensitivity Analysis

To enhance the robustness of the analysis, the MILP model is tested under multiple scenario analyses representing different carbon pricing policies and regulatory intensities. Additionally, sensitivity analyses are conducted to evaluate how variations in key parameters, such as production costs, transportation costs, and technology investment costs, affect the optimal solutions and strategic recommendations. This approach ensures comprehensive insights into the impacts and strategic implications of evolving market conditions and regulatory environments.

The model incorporates three prominent carbon pricing scenarios defined by the IEA (2024): the Stated Policies (STEPS) scenario, the Announced Pledges (APS) scenario, and the Net Zero Emissions (NZE) scenario. Each scenario provides varying carbon price trajectories that influence optimal supply chain configurations. STEPS includes only policies already enacted or advanced in adoption, APS adds all announced policies regardless of feasibility, and NZE outlines the measures necessary to achieve net-zero emissions by mid-century.

To capture realistic regional dynamics, carbon prices are differentiated by country or regional cluster, reflecting both current commitments and expected policy developments. In STEPS, carbon prices are set on a country-specific basis. At the same time, in APS and NZE, countries are grouped into three categories – advanced economies with net-zero pledges, emerging markets with pledges, and other emerging markets – based on IMF classifications (International Monetary Fund, 2023) and International Energy Agency (IEA) pledge data (International Energy Agency, 2025). Prices are applied to emissions from cement production and evolve according to intervals drawn from the IEA scenarios.

For EU jurisdictions, the model also adjusts effective carbon costs to account for the phase-out of free allowances under the EU ETS, using the CBAM phase-out factors (European Union, 2023). To model annual carbon costs, prices from the IEA scenarios, provided at intervals, are assigned to the closest corresponding year. For example, the price given for 2030 is applied to the years 2028 through 2032, while the price for 2035 is applied to the years 2033 through 2037. This structured approach ensures the model captures regionally differentiated and policy-relevant carbon costs, enabling a robust analysis of the financial implications of decarbonisation strategies under varied regulatory futures. Table 2 presents the carbon prices of the different scenarios.

Table 2: Carbon prices in USD indexed to 2025 per ton under IEA scenarios by region and year (IEA, 2024).

Scenario	**2030**	**2035**	**2040**	**2050**
STEPS (Stated Policies)				
EU	147	152	156	165
China	41	45	48	54
Chile and Colombia	22	25	29	29
Korea	59	68	76	93
Canada	132	132	132	132
APS (Announced Pledges)				
Advanced economies with NZ pledges	141	167	183	209
Emerging markets with NZ pledges	42	68	115	167
Other emerging markets	–	6	18	49
NZE (Net Zero Emissions by 2050)				
Advanced economies with NZ pledges	147	188	215	262
Emerging markets with NZ pledges	94	131	167	209
Other emerging markets	16	26	36	57

5 Results

This section presents the outcomes of the MILP model developed to optimise investment and distribution decisions in the cement industry under varying carbon pricing and regulatory scenarios. The analysis focuses on evaluating the impact of the CBAM across three policy scenarios defined by the IEA (2024): the STEPS, the APS, and the NZE.

Each scenario is analysed by comparing outcomes with and without the CBAM, enabling an assessment of how carbon regulation shapes the geographic allocation of carbon capture investments and the global distribution of cement. The STEPS scenario serves as the base case. It is examined in detail, followed by scenario-specific comparisons under APS and NZE to illustrate how regulatory stringency interacts with investment and trade dynamics.

As the distribution results in this section are presented in absolute volumes, it is important to note two key modelling assumptions. First, market share constraints limit the maximum distribution to each region. Second, this study assumes no construction or acquisition of additional production capacity, meaning supplier output remains capped at existing capacities throughout the 25-year modelling horizon. Together, these assumptions set an upper bound on the distribution volumes, which explains the plateaus observed in certain years.

To ensure robustness, the model outcomes are supplemented by a sensitivity analysis evaluating how changes in key cost parameters affect investment decisions and cement flows. Together, these results offer insights into how regulatory instruments and cost structures shape decarbonisation strategies, both for firms and policymakers operating in globally exposed sectors, such as the cement industry.

The results section begins with a detailed description of the case study framework, followed by the presentation and discussion of the scenario outcomes that follow.

5.1 Case Study: Heidelberg Materials

Although the MILP framework is broadly applicable, this analysis focuses on Heidelberg Materials to ground the model in a concrete, data-rich example. Heidelberg Materials was chosen for its extensive global network, clear decarbonisation targets, and pioneering deployment of carbon capture systems.

Key inputs are tailored to Heidelberg Materials' operations. Production facility nodes F correspond to its published cement plants, and regional market-share limits (Equation 12) draw on the company's annual fact sheets from 2021–2024 (Heidelberg Materials, 2025, 2024b, 2023). It sets each continent's shipment cap β_c to the highest historical share of Heidelberg's deliveries, ensuring that future flows remain within plausible bounds while permitting flexibility in reallocation.

Heidelberg's existing post-combustion capture unit at Porsgrunn is hardwired into the model through an additional constraint, namely:

$$y_{\text{PorsgrunnP}t} = 1 \qquad \forall\, t \in T \tag{13}$$

Its already-paid capital cost is excluded from the optimisation, reflecting the prior investment already made.

Finally, the annual investment ceiling Θ is set equal to Heidelberg Materials's reported 2024 outlay on property, plant, and equipment (Heidelberg Materials, 2024a). All other cost inputs, covering production, transportation, and the transport and storage of captured carbon, are sourced from the literature. These bespoke calibrations ensure that the scenarios and sensitivity tests accurately reflect the real-world economic and regulatory environment that Heidelberg Materials will face.

5.2 STEPS Scenario (Base Case)

The STEPS scenario, which reflects existing carbon pricing policy trajectories, establishes baseline investment and distribution patterns prior to the implementation of the CBAM. By contrasting outcomes "without the CBAM" and "with the CBAM", the analysis reveals how CBAM modifies investment locations and cement distribution patterns.

Under the STEPS assumptions, without the CBAM, no new carbon capture investments become economically viable beyond existing operational facilities. However, when the CBAM is implemented, 10 new carbon capture and storage retrofits become financially attractive. These investments predominantly cluster in South and Southeast Asia, as well as Central Asia, as depicted geographically in Figure 1. Notably, European locations remain absent from new investments, indicating that European production costs, even with the CBAM, are too high to justify retrofitting without additional policy support.

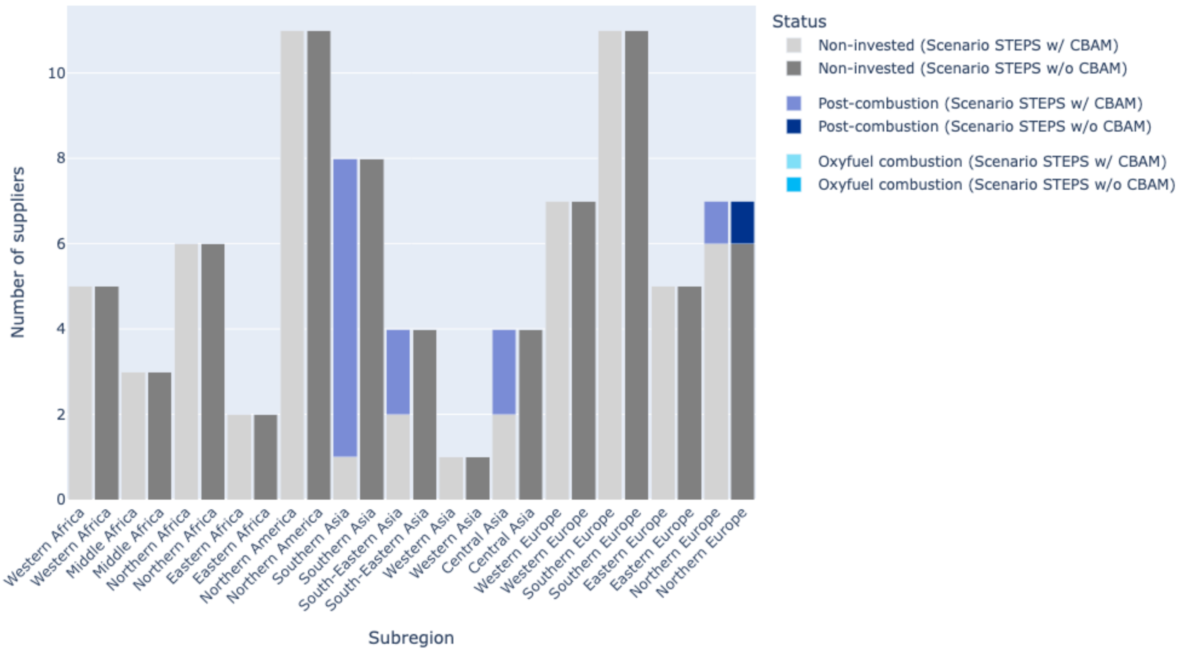


Figure 1: Geographical distribution of carbon capture retrofit investments under the STEPS scenario, comparing outcomes without and with the CBAM.

The bar charts illustrate how much of Europe's internal demand is allocated among supplier regions (see Figure 2 and Figure 3). Distribution patterns under STEPS reveal significant differences before and after the implementation of the CBAM. Initially, without the CBAM, European demand is substantially met by domestic producers due to their lower carbon costs, as illustrated in Figure 2. With the phase-out of free EU ETS allowances, Europe's market share becomes increasingly filled by cost-advantaged Asian and African suppliers.

With the CBAM active from 2026, imported cement becomes less competitive in Europe due to additional carbon costs, allowing European producers to reclaim a substantial portion of the domestic market share (Figure 3). In the initial years after CBAM implementation, Europe's share shows a slight dip, which can be attributed to transitional dynamics as the policy takes

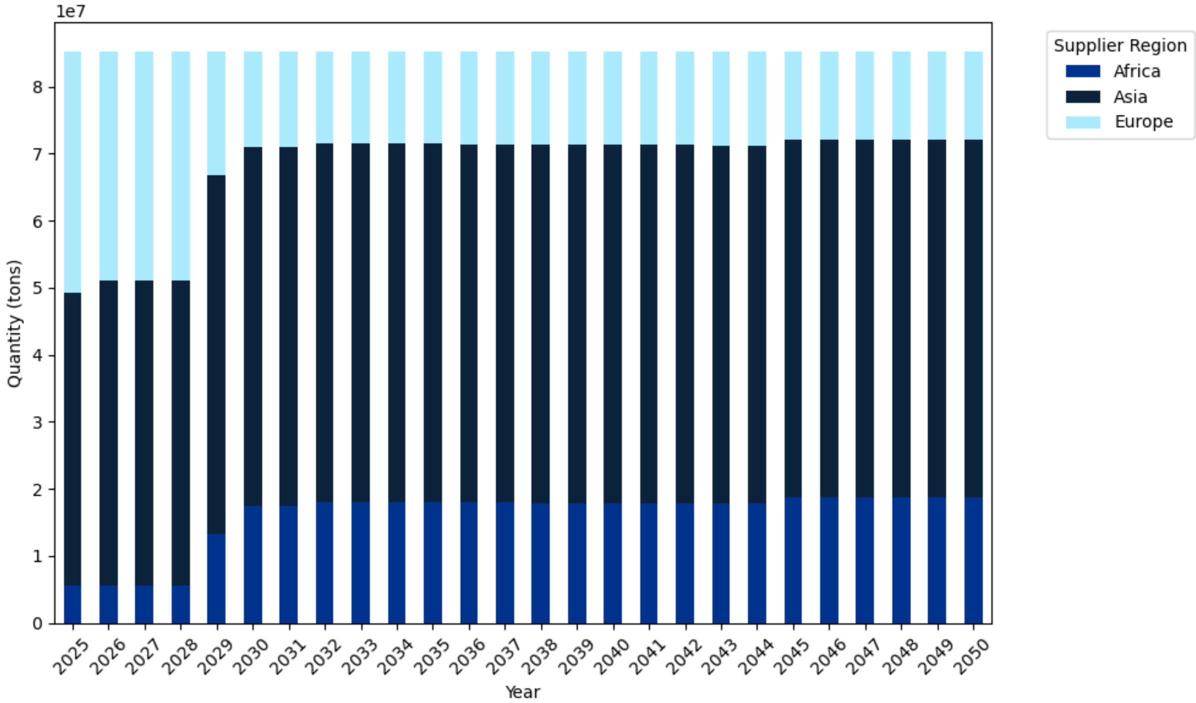


Figure 2: Allocation of European cement demand by supplying region under the STEPS scenario without the CBAM.

effect. However, from 2028 onward, distribution towards Europe increases again, coinciding with the first investments in carbon capture becoming operational and enhancing the competitiveness of European production.

The distribution bars reveal that although Asian-produced cement briefly gains market share in Europe as its capture retrofits come online, this advantage shifts in 2038. During this period, African-produced cement increased its exports to Europe, while shipments from Asia declined. This change is linked to regional carbon price trajectories: as carbon prices in the Republic of Korea rise faster than in the EU (see Table 2), Heidelberg Materials redirects Asian production towards Korea to maximise margins, reallocating African output to European markets instead. This dynamic is further illustrated in detailed heatmaps (Figure 4), which show evolving trade patterns, including increased intra-European distribution and fluctuating imports from Asia and Africa over time.

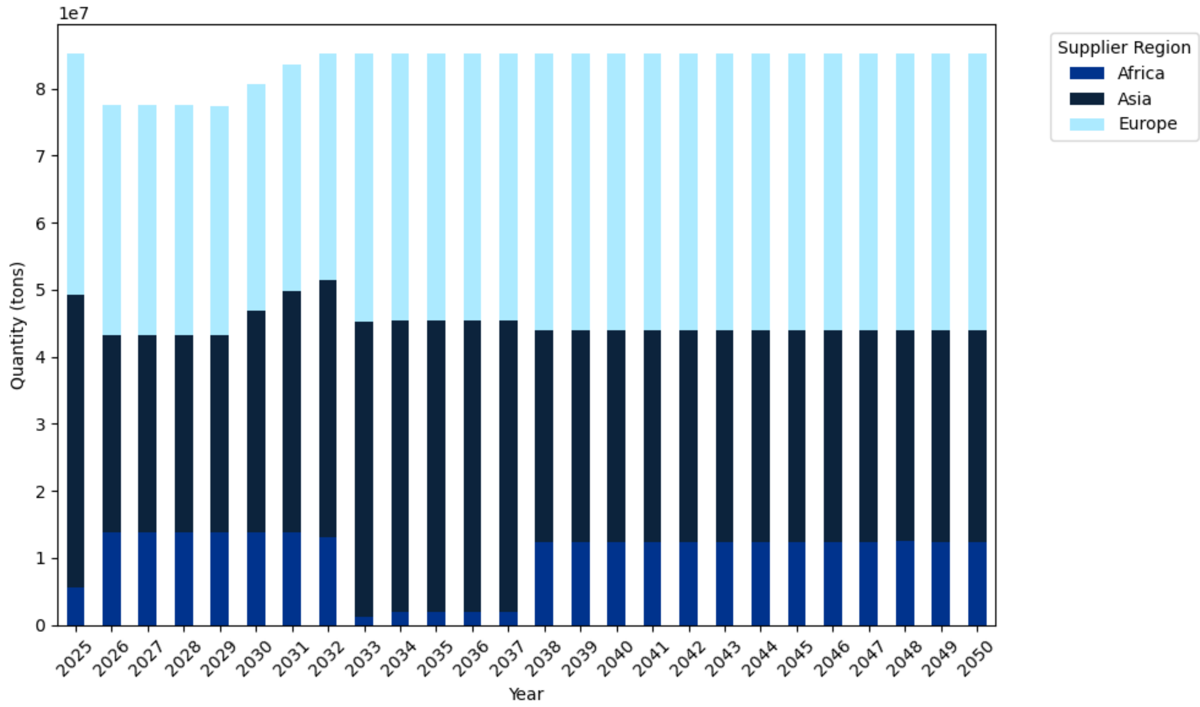


Figure 3: Allocation of European cement demand by supplying region under the STEPS scenario with the CBAM implemented from 2026.

The comprehensive STEPS scenario analysis highlights how the CBAM significantly reshapes strategic investments and global cement distribution patterns, as well as alters competitive dynamics within European markets. These insights highlight critical strategic considerations for industry stakeholders and policymakers, emphasising the need for targeted policies to support European decarbonisation efforts.

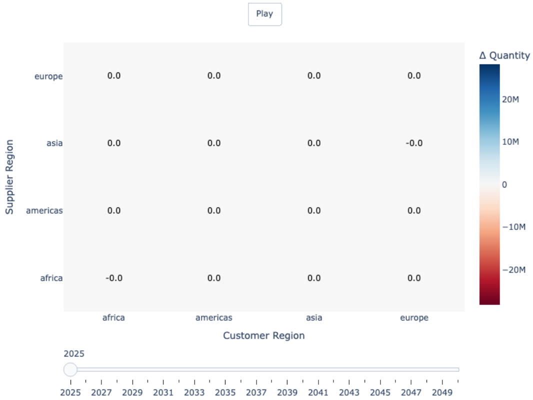
5.3 Scenario Analysis

Scenario analyses involving the APS and NZE scenarios provided a comparative assessment of varying carbon pricing intensities and their strategic implications.

Scenario analysis is crucial for evaluating the impact of various future policy pathways on strategic decisions within the cement supply chain. Using three scenarios from the IEA (2024) – STEPS, APS, and NZE – this study examines a range of carbon pricing trajectories, from conservative (base case) to highly ambitious. These scenarios illustrate how shifts in international climate policy could affect the competitiveness of cement producers under the CBAM, offering insights into how policy convergence or divergence may alter trade flows and investment strategies. In the following analysis, the APS and NZE scenarios are compared with the STEPS scenario.

5.3.1 APS Scenario

Under the APS scenario, reflecting pledged carbon pricing commitments, investment and distribution patterns initially established without the CBAM differ significantly once the CBAM is applied.



(a) Snapshot year 2025.

(b) Snapshot year 2030.

(c) Snapshot year 2035.

(d) Snapshot year 2040.

(e) Snapshot year 2045.

(f) Snapshot year 2050.

Figure 4: Heatmaps of shipment-volume differences (CBAM minus no CBAM) by supplier (rows) and customer (columns) at five-year intervals. Blue values indicate increased shipments under CBAM; red indicates reductions; white indicates negligible change.

In APS, higher carbon pricing makes carbon capture retrofits economically viable even without the CBAM. The model identifies 10 retrofit locations consistently viable under both scenarios, primarily located in Asia, alongside two in Europe and one in North America (Figure 5). Without the CBAM, additional investments are expected in Europe, driven by the relatively high EU ETS prices.

Higher carbon pricing under APS makes carbon capture retrofits economically viable even without the CBAM. The model identifies 10 retrofit locations consistently selected under both scenarios, primarily clustered in Asia, with two in Europe and one in North America (Figure 5). Without the CBAM, additional investments are expected in Europe, as higher EU ETS prices make retrofitting European plants more competitive. However, once the CBAM is activated, investments shift toward lower-cost regions, particularly Southern and Central Asia, as well as parts of Northern and Western Africa. This shift occurs because the CBAM internalises carbon costs on imports, reducing the relative advantage of European plants and making overseas retrofits more profitable. As a result, the CBAM under APS leads to a more geographically dispersed investment pattern but also suggests a weaker incentive for decarbonisation investment within Europe itself.

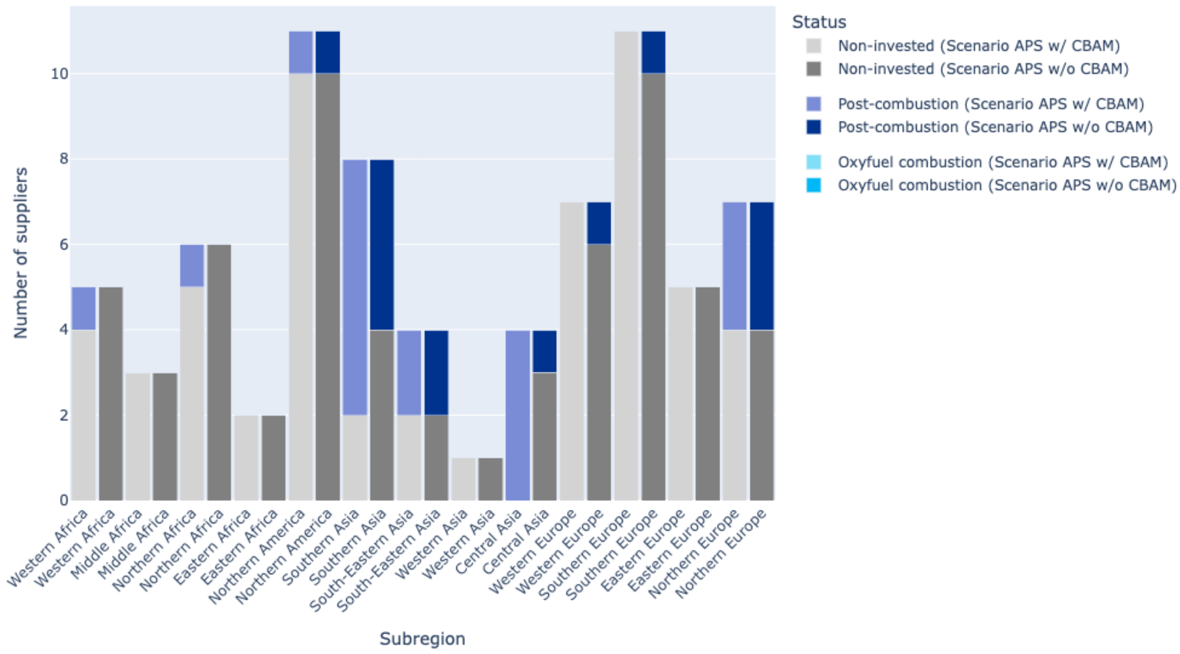


Figure 5: Geographical distribution of carbon capture retrofit investments under the APS scenario, comparing outcomes without and with the CBAM.

Distribution under APS without the CBAM initially favours Asian imports into Europe but quickly transitions to increased European sourcing, as shown in Figure 6. This can be attributed to emerging carbon pricing policies, which narrow the gap between lower-cost regions and Europe, making it less attractive to distribute there. The introduction of the CBAM delays Europe's attainment of its maximum market share, reflecting a reduced advantage for high-carbon imports. Interestingly, while African exports diminish under the CBAM, Asian producers, supported by additional retrofits, increase their European market share slightly, underscoring the effectiveness of targeted low-cost investments but also the risk that import levies may not fully protect European producers if foreign investment sites are more economically attractive and can competitively serve the European market (Figure 7).

The APS scenario demonstrates how enhanced carbon pricing incentivises retrofits and reshapes global cement distribution. The addition of the CBAM significantly influences project locations and distribution, underscoring the strategic importance of integrated, forward-looking

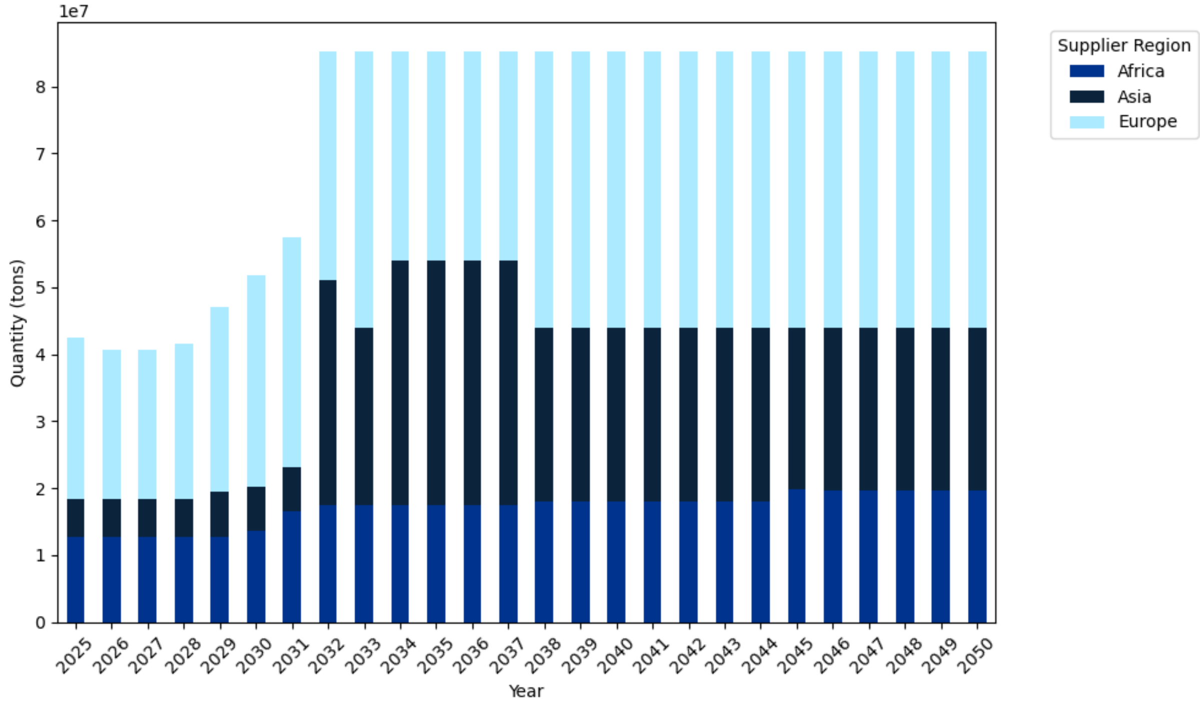


Figure 6: Allocation of European cement demand by supplying region under the APS scenario without the CBAM.

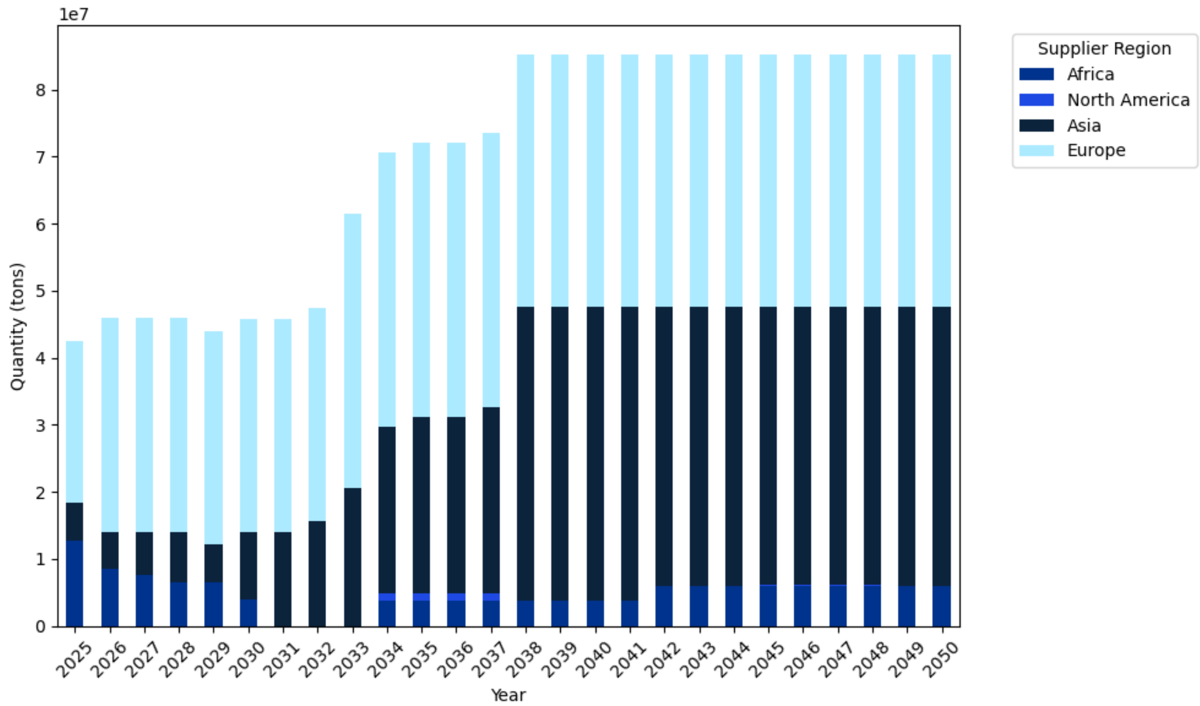


Figure 7: Allocation of European cement demand by supplying region under the APS scenario with the CBAM implemented from 2026.

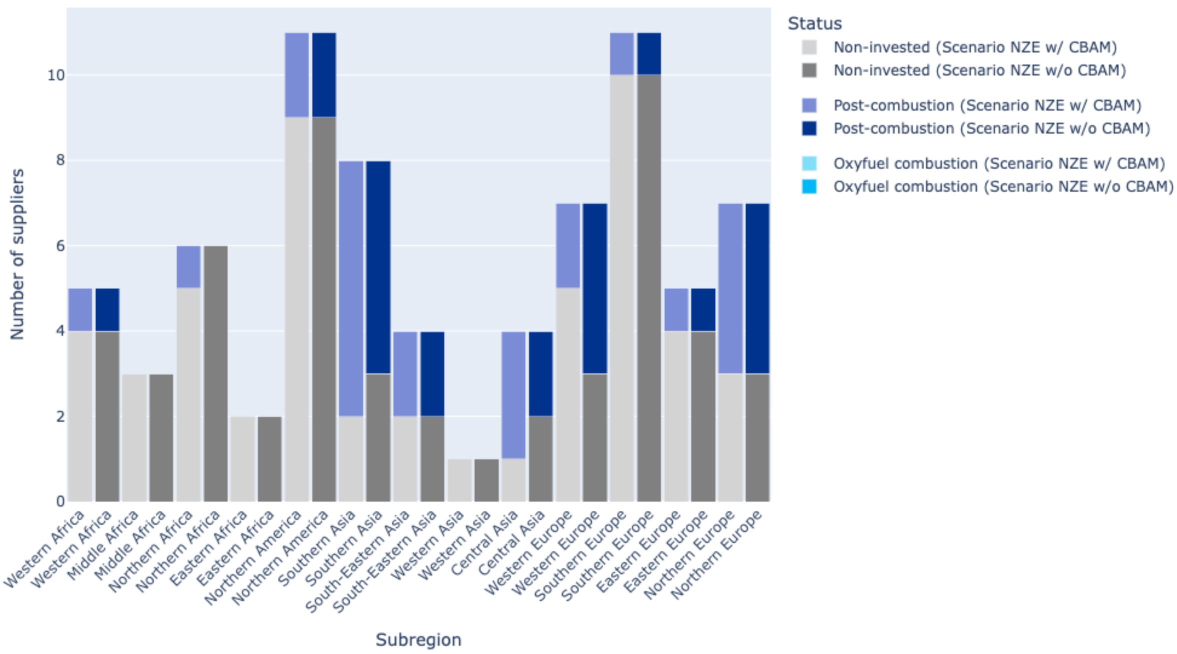


Figure 8: Geographical distribution of carbon capture retrofit investments under the NZE scenario, comparing outcomes without and with the CBAM.

decision-making frameworks. This highlights the need for complementary support from the EU to ensure that decarbonisation efforts within its jurisdiction remain economically viable and globally competitive.

5.3.2 NZE Scenario

The NZE scenario represents an aggressive global decarbonisation trajectory where all major economies reach net-zero emissions by 2050, significantly elevating carbon pricing worldwide.

Under NZE, even without the CBAM, substantial carbon capture investments become economically viable in Europe due to high domestic carbon prices, resulting in a significant concentration of projects on the continent (Figure 8). The activation of the CBAM shifts investments from Western Europe to lower-cost regions such as Central Asia, Northern Africa, and Southern Asia. Without the CBAM, there is little incentive to invest in production outside Europe, as imported cement does not face carbon-related costs. In that case, producers are better off investing within Europe to optimise their supply chains. However, once the CBAM is activated, carbon costs are effectively internalised for imports as well. This makes investments in lower-cost regions with more favourable emissions profiles and production economics more attractive, allowing producers to supply the European market more profitably from abroad.

Without the CBAM, Europe's market share is always on the low side. This is partly because it is more beneficial to send the produced cement to other regions. During the phase-out of the free allowances, imports from Asia and Africa increase due to the introduction of aggressive domestic carbon pricing. Eventually, the European-produced cement is distributed more inter-regionally again due to investments being made in Europe (Figure 9). The application of

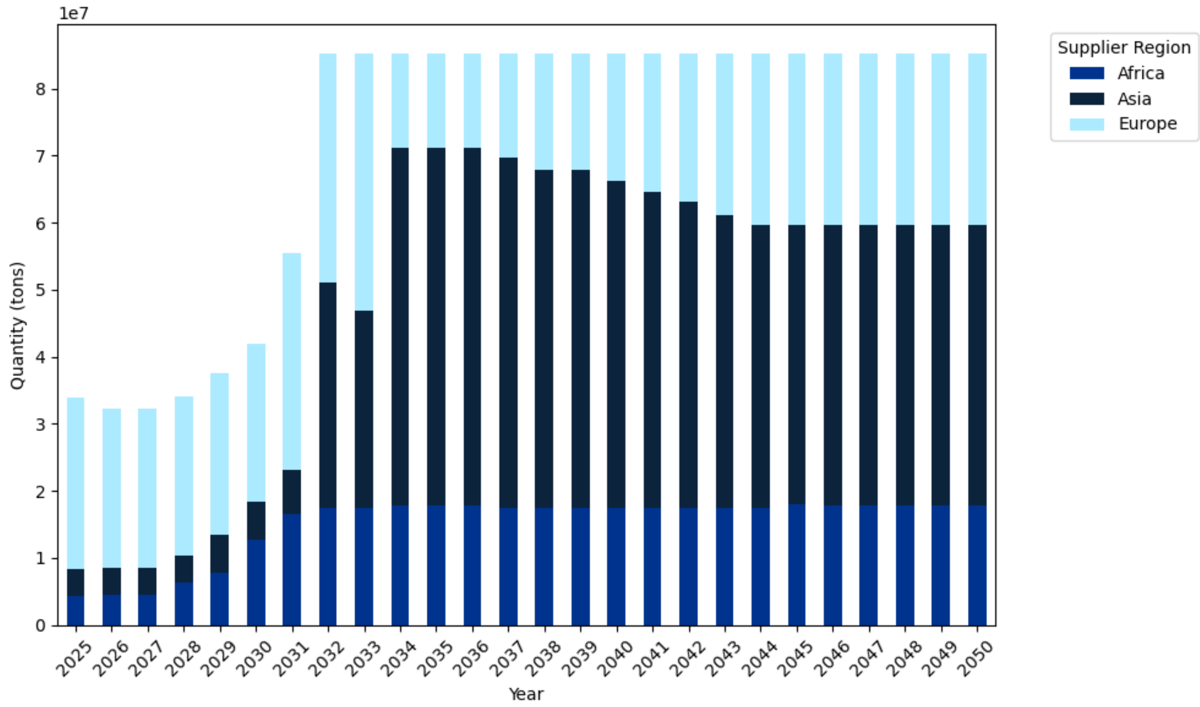


Figure 9: Allocation of European cement demand by supplying region under the NZE scenario without the CBAM.

CBAM temporarily slows Europe's market recovery but significantly impacts Asian and African flows, redirecting early volumes to inter-regional markets. Ultimately, the model illustrates CBAM's crucial role in reshaping global trade dynamics, enhancing European self-sufficiency, and balancing imports and domestic production strategically (Figure 10).

The NZE scenario highlights the compounded impact of aggressive carbon pricing and the CBAM. High domestic carbon prices alone incentivise European retrofits, but the introduction of the CBAM redirects projects to cost-effective regions abroad. Despite these shifts, Europe continues to maintain a dominant market share in the cement distribution sector. The scenario confirms that while NZE policies strongly support decarbonisation, instruments like the CBAM remain pivotal in influencing global supply dynamics but risk shifting decarbonisation investments outside the EU.

5.4 Sensitivity Analysis

To evaluate the robustness of the model outcomes, sensitivity analyses were conducted on four cost parameters: production costs, transportation costs, transport and storage costs, and investment costs. These were systematically scaled across predefined multipliers and tested under both CBAM and no-CBAM policy scenarios. The key effects on investment decisions are summarised in a series of tornado diagrams, each showing the deviation in cumulative investments across regions at the end of the planning horizon (see Figure 11, Figure 12, Figure 13, and Figure 14).

The sensitivity analysis reveals a pronounced responsiveness of investment decisions to variations in production costs compared to the baseline scenario. Without the CBAM, reductions in production costs make additional projects viable exclusively within Europe, particularly in

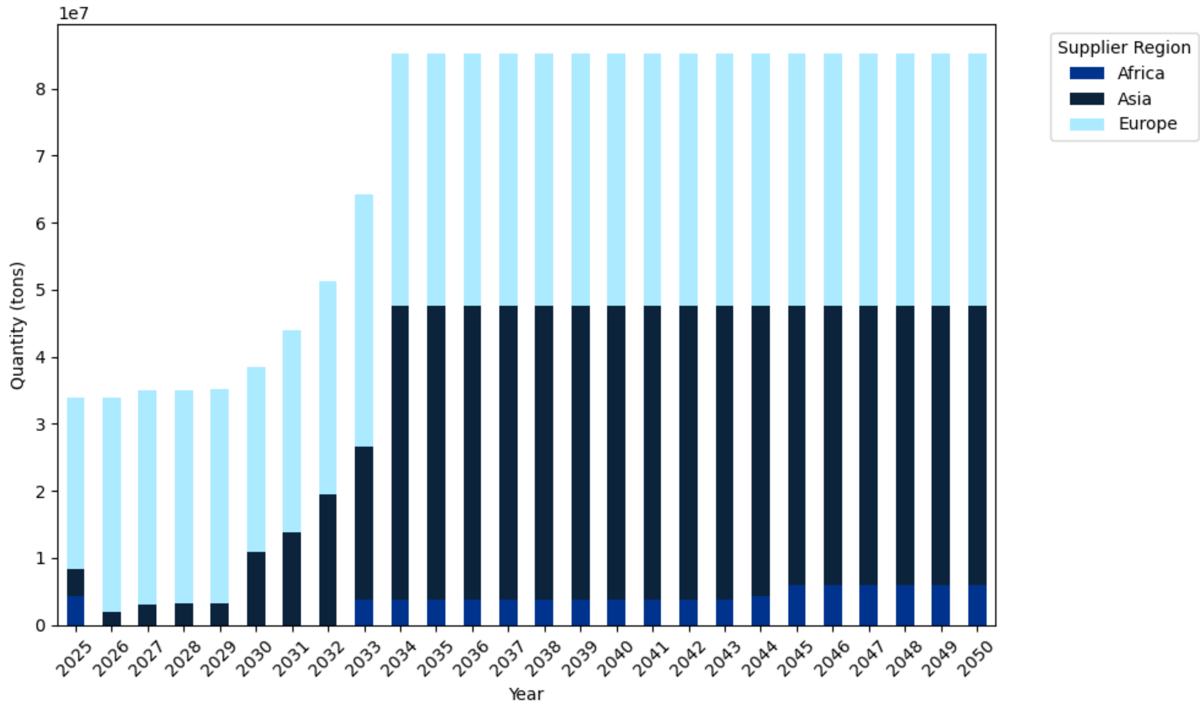


Figure 10: Allocation of European cement demand by supplying region under the NZE scenario with the CBAM implemented from 2026.

Northern and Western subregions. These additional investments only emerge at substantially lowered cost factors relative to the baseline; increases in production costs beyond the baseline do not alter the already limited investment portfolio, as illustrated in Figure 11. This indicates that, absent a carbon border adjustment, Europe's potential to secure capture investments is constrained, with production cost assumptions directly governing the feasibility of domestic decarbonisation efforts.

Under the CBAM, sensitivity to production costs intensifies: reductions below the baseline trigger a marked reallocation of investments from Southern Asia toward Europe and Northern Africa. The tornado diagrams in Figure 12 show investment gains in Europe and Africa under lowered cost scenarios, while higher-than-baseline factors cause progressive withdrawal of projects. These patterns underscore that the model reacts to changes in production costs; the required cost adjustments to make meaningful shifts in investment decisions are relatively large, indicating that the model is responsive but not overly sensitive to modest cost fluctuations. This suggests that the model provides stable and robust investment guidance, with decisions unlikely to swing dramatically based on minor uncertainties in production cost estimates.

In contrast, transportation cost changes did not affect investment siting under either policy regime. This invariance is reflected in the flat profiles of the tornado diagrams (and is therefore not shown), confirming that freight rate uncertainty does not affect the geographical allocation of capture retrofits. Distribution outcomes were also only modestly impacted: lower freight costs modestly accelerated African imports under no-CBAM conditions, while the CBAM offset these effects entirely, preserving a stable European supply share.

Transport and storage costs showed limited but observable sensitivity to changes. As indicated by the tornado diagram in Figure 13, a 50% reduction in transport and storage costs

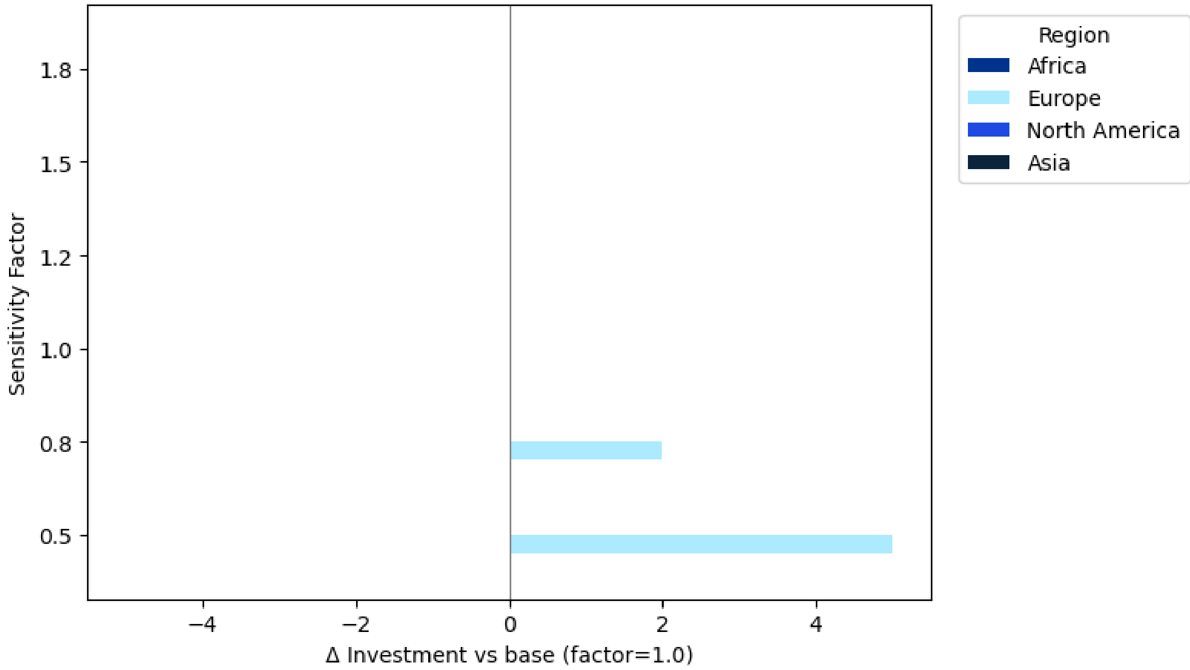


Figure 11: Tornado diagram showing the sensitivity of cumulative carbon-capture investments to production cost variations under the no-CBAM scenario. Each bar represents the change in total investments by region at 2050 relative to the baseline.

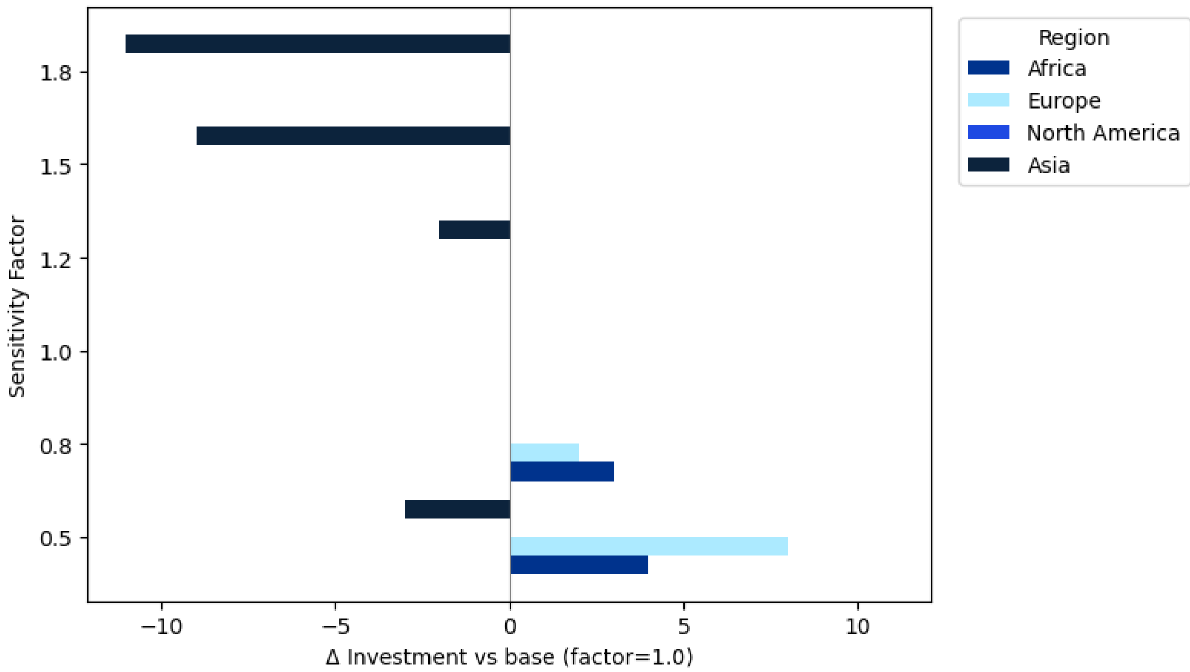


Figure 12: Tornado diagram showing the sensitivity of cumulative carbon-capture investments to production cost variations under the CBAM scenario. Bars indicate regional investment gains or losses by 2050 relative to the baseline.

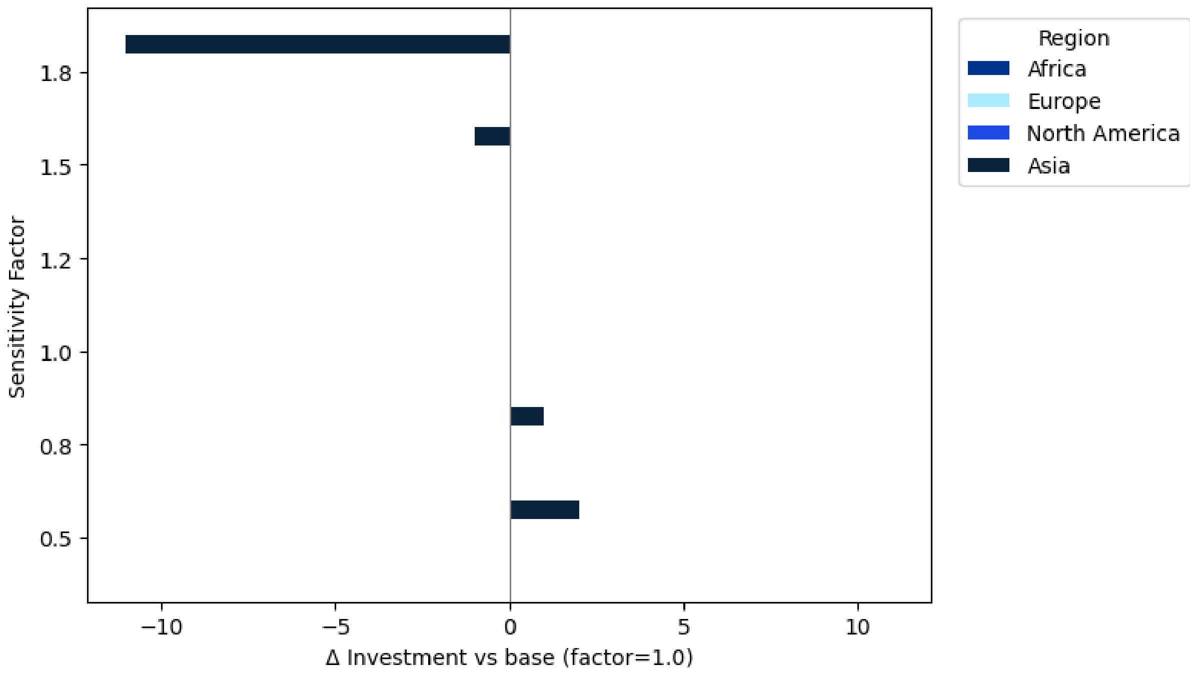


Figure 13: Tornado diagram showing the sensitivity of cumulative carbon-capture investments to variations in transport and storage costs under the CBAM scenario. Bars represent changes in regional investments by 2050 relative to the baseline.

enabled the addition of two projects in Central and Southern Asia. Conversely, the progressive increase in costs rendered these sites uneconomic. While the magnitude of these shifts is modest, the results underscore that such cost parameters can influence investment decisions under regulatory pressure.

Finally, investment cost uncertainty produced some project substitutions. Lower capital costs shifted investments within Asia, whereas a 35% cost increase rendered all CBAM-induced retrofits uneconomic, as reflected in the steep drop shown in the tornado chart Figure 14. Moderate shifts in regional import shares accompanied these changes but did not materially affect Europe's overall supply balance.

In summary, the sensitivity analysis confirms that production costs are the primary driver of both investment and distribution outcomes, determining where carbon capture investments occur relative to the baseline assumptions. While transportation costs alone do not affect investment siting, transport and storage costs, as well as investment costs themselves, can influence the viability of marginal projects under the CBAM scenario. Notably, the model demonstrates stability, suggesting that minor uncertainties or modest fluctuations in cost estimates are unlikely to result in significant deviations from optimal strategies. This robustness enhances confidence in the model's guidance for long-term planning. Still, these findings underscore the importance of accurately estimating production and capital costs for reliable modelling of decarbonisation strategies in the context of carbon border adjustments, enabling industry stakeholders and policymakers to craft robust and cost-effective climate policies.

Across all scenarios, carbon pricing trajectories and the presence or absence of the CBAM significantly influence both strategic investment decisions and patterns of cement distribution.

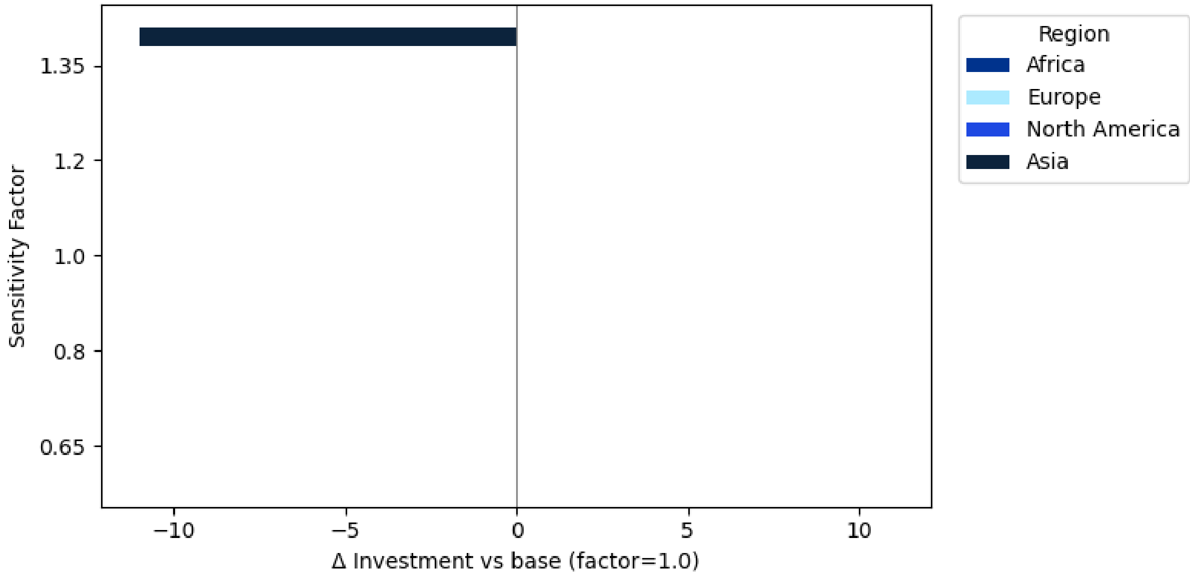


Figure 14: Tornado diagram showing the sensitivity of cumulative carbon-capture investments to variations in capital investment costs under the CBAM scenario. Bars indicate changes in regional investments by 2050 relative to the baseline.

In the STEPS scenario, which reflects current policy trends, the CBAM proves critical in making any new carbon capture investments viable. Without the CBAM, Europe is becoming increasingly reliant on low-cost foreign producers. The application of the CBAM partially reverses this trend, enabling select domestic producers to retain their market share.

Under the APS scenario, stronger carbon pricing already incentivises capture retrofits, including in Europe. However, the CBAM still plays a decisive role in determining where investments are located, often shifting them away from Europe toward more cost-effective Asian facilities. In contrast to the STEPS and NZE scenarios, the CBAM regulation under APS has a limited impact on Europe's distribution shares, indicating that the higher carbon prices in specific jurisdictions alone drive most of the trade patterns in this scenario.

In the NZE scenario, high global carbon prices drive strong retrofit adoption within Europe even without the CBAM. The addition of the CBAM fine-tunes the global allocation of projects and strengthens Europe's trade balance. Nevertheless, it reveals that competitive foreign producers can still profitably serve European markets when equipped with carbon capture capacity.

Overall, the CBAM consistently alters the investment landscape by internalising carbon costs for imports. Its effects are most pronounced under moderate carbon pricing (STEPS), diminish somewhat under APS, and function as a secondary influence under NZE. The findings emphasise the importance of integrated policy and investment planning, particularly for European decarbonisation strategies aiming to balance climate ambition with industrial competitiveness.

It is essential to note that the MILP framework employed in this study assumes constant marginal costs for production, transportation, and retrofitting throughout the entire modelling horizon. This linearity simplifies the analysis and ensures computational efficiency but may overlook real-world dynamics such as economies of scale, volume discounts, or threshold effects that could influence investment decisions.

6 Conclusion

This study develops and applies a Mixed-Integer Linear Programming framework to optimise investment and distribution decision-making in the cement industry under varying carbon pricing regimes, with a specific focus on the EU's Carbon Border Adjustment Mechanism (CBAM). By integrating long-term investment decisions in carbon capture technologies with annual distribution flows, the model contributes methodologically to existing literature by explicitly capturing interdependencies among investment decisions, technology selection, and international trade logistics. Capturing the interdependencies among investment timing, technology selection, and trade strategies, the model provides a realistic and actionable decision-support tool for both cement producers and policymakers.

Methodologically, this research advances the field by embedding key regulatory features – such as CBAM-induced cost differentials – directly into the optimisation framework. The model is distinguished by its integration of technology-specific investment decisions, distribution strategies, and policy-aligned cost assumptions, enabling the simulation of realistic industry responses to evolving climate policies.

The study applies this framework to Heidelberg Materials across three distinct International Energy Agency (IEA) scenarios (STEPS, APS, NZE). Results from three IEA-aligned scenarios demonstrate that the CBAM fundamentally alters the feasibility and location of carbon capture investments. In the STEPS scenario, the CBAM is the decisive trigger that enables retrofits that would otherwise remain unprofitable, while in APS, elevated carbon prices make many projects viable even without the CBAM; nonetheless, the mechanism still influences global investment allocation. Under NZE's stringent carbon prices, significant investments occur in Europe regardless of the CBAM, with the regulation fine-tuning project distribution toward the lowest-cost regions. Within the STEPS and NZE scenarios, the model shows how the CBAM reshapes Europe's trade balance and investment attractiveness. The CBAM has no significant impact on the trade balance in the APS case; nevertheless, it does influence the optimal investment locations, which are in all three cases primarily located in low-cost regions – such as Asia.

For cement producers, the findings underscore the critical importance of monitoring carbon pricing developments and incorporating them into distribution strategies to minimise exposure to rising carbon-related costs. The model developed in this study can serve as a valuable tool for guiding informed decision-making, enabling firms to optimally respond to evolving carbon pricing mechanisms and advance the decarbonisation of their supply chains. Companies should also establish robust plant-level data systems to accurately track production costs and emissions, thereby improving both strategic investment decisions and the reliability of modelling results. Additionally, such systems can help ensure industry readiness for potential future reporting requirements.

For policymakers, the results indicate that while the CBAM effectively levels the playing field by internalising carbon costs for imports in two of the three scenarios, it may also incentivise decarbonisation investments outside Europe. Complementary support measures, such as targeted subsidies or tax incentives for carbon capture in higher-cost EU regions, could better align the EU's protective intent with Europe's climate objectives. The model developed in this study can serve as a valuable tool for analysing industry responses to newly introduced or evolving regulations.

Future research could build upon this model by explicitly integrating additional emission-reduction strategies beyond carbon capture, such as the use of alternative fuels (e.g., biomass or waste-derived fuels) or clinker-substitution technologies. Exploring these strategies would allow a comprehensive assessment of multiple decarbonisation pathways within the cement supply chain and their interactions under various carbon pricing policies. Additionally, future work should assess the effectiveness and economic implications of targeted subsidy schemes – such as CAPEX grants, OPEX support or a hybrid design – to specifically stimulate retrofits in European plants that are otherwise economically marginal under current CBAM settings. Finally, enhancing the model's practical accuracy could be achieved by incorporating detailed, plant-level operational data, gathered through industry collaborations, thereby capturing site-specific constraints, retrofit feasibilities, and dynamic cost structures. Such granular inputs would significantly improve the model's realism, making it a highly robust and actionable decision-support tool for cement producers navigating the evolving and complex global regulatory landscape.

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