# Price effects of carbon policy

Greenlight Thesis

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October 3, 2024

TU Delft Delft University of Technology

Challenge the future

# Acknowledgement

I would like to express my gratitude to those who have supported me throughout my MSc thesis journey. Firstly, I would like to thank Dr. Enno Schröder for his guidance, support, and encouragement, as well as for providing me with the opportunity to pursue a topic that deeply motivates me. I would also like to extend my appreciation to Dr. Linda Kamp, without whose support, clear feedback, and encouragement this thesis would not have been possible.

This thesis represents the end of my journey at the Delft University of Technology, and I am immensely thankful to the Faculty of Aerospace Engineering, where I completed my Bachelor's, as well as the MSc programme of Sustainable Energy Technology, where I have had the opportunity to developed myself over the last years.

Lastly, this journey has not always been easy, ranging from the normal challenges of studying to persevering through the pandemic. I would like to extend my appreciation to those who supported me along the way—my family, loved ones, friends, teammates, and everyone else who made my time at TU Delft some of the most enriching and enjoyable years of my life thus far.

*Patrick Sheppard - 3rd of October 2024*

# Abstract

Carbon pricing is a common and constantly changing policy tool with the goal of stimulating the reduction of carbon dioxide emissions and the transition to cleaner technologies. The combination of a carbon tax and the new Carbon Border Adjustment Mechanism (CBAM) is causing price effects in the EU. There is currently a lack of research using the latest high-granularity data to identify price effects by country and sector in the EU. Additionally, only a few methodologies exist to validate and enhance models of current carbon policy price effects. This thesis estimates the price effects of carbon taxation across EU sectors and countries using 2021 FIGARO data with high sector granularity. Using traditional input-output modelling the tax was first applied to value-added - the standard method - and subsequently the approach of taxing intermediate sales was explored. The results from the value-added method were extended to estimate changes in trade flows and subsequently placed into the context of the broader political economy. Additionally, the outcomes from the intermediate sales method were compared to those from the value-added method. This showed that the EU will experience an average price increase of 1.26%, and CBAM changes a competitive disadvantage from -0.98% to a 1.46% competitive advantage. It is therefore seen that price increases remain moderate, and CBAM achieves its goal of protecting the EU's competitiveness. However, for a carbon tax and CBAM to be fully effective in stimulating a transition to cleaner technologies, they should be implemented in combination with subsidies, investment in markets and infrastructure, as well as effective dissemination of research and development. The model was limited to examining the effects within the EU, and more research is needed to expand it to understand the impacts on trade partners. Additionally, further analysis is needed to understand the mechanics of the tax on intermediate sales method.

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# List of Symbols

| | |
|---|---|
| $\lambda_{\max}$ | Largest eigenvalue of matrix **A** |
| **A** | Matrix of technical coefficients |
| **f** | Vector of final demands |
| **i** | Vector of ones |
| $\mathbf{L}'$ | Transposed Leontief matrix |
| **L** | Leontief inverse matrix |
| **P** | Price vector |
| **T** | Diagonal matrix for taxing intermediate sales |
| **t** | Vector of tax revenues for all sectors |
| $\mathbf{v_c}$ | Vector of value added per unit of output of a sector |
| $\mathbf{v_{c_{tax}}}$ | Vector of value added including tax for all sectors |
| **x** | Vector of total outputs for all sectors |
| **Z** | Matrix of intermediate sales |
| $\tau$ | Sectoral tax rate for intermediate sales |
| det | Determinant of a matrix |
| $a_{ij}$ | Technical coefficient representing the flow from sector $i$ to sector $j$ |
| $CO_2$ | Carbon dioxide emissions |
| $f_i$ | Final demand in the economy for the output of sector $i$ |
| $t_j$ | Tax revenue for sector $j$ |
| $t_r$ | Tax rate per tonne of $CO_2$ |
| $v_{c_j}$ | Value added per unit of output for sector $j$ |
| $v_{c_{tax}}$ | Value added per unit output including tax for a sector |
| $x_i$ | Total output of sector $i$ |
| $z_{ij}$ | Flow from sector $i$ to sector $j$ |

# 1 | Introduction

Carbon emissions pose a significant threat to a safe and habitable world. Incorporating the cost on the economy due to the negative impacts of carbon emissions by internalizing the negative externalities is necessary to combat this challenge. Economists widely advocate for carbon pricing mechanisms, for example, Emissions Trading Systems (ETS) and Carbon Border Adjustment Mechanism (CBAM), to incentivise the transition to sustainable energy technologies and reduce overall emissions (Dechezleprêtre and Sato, 2017, Cameron and Baudry, 2023). CBAM, which is currently being implemented, is poised to have substantial economic implications. With a constantly evolving picture and inconclusive research, this field sees a constant emergence of new data and ongoing policy implementation (Naomi Newman, 2022).

After the Kyoto Protocol in 1997, the European Union (EU) implemented and developed a carbon pricing strategy (European Comission, n.d.-b). This was to attach a price to every tonne of Carbon Dioxide ($CO_2$) where this price internalizes the negative externalities of climate change and stimulates the development of technologies that would lead to a greener society (European Union, 2003). This was implemented by stating that for every tonne of $CO_2$ emitted an economic actor had to purchase a "carbon credit" as a way of paying for these emissions. This formed the basis for ETS where credits could be bought or sold by economic actors depending on the quantity of their emissions. For the remainder of this thesis, ETS and carbon tax refer to the same concept: a price on carbon. The EU introduced ETS in 2005, starting with very low carbon prices and was implemented in three phases. Initially, only a few industries were included, with some credits needing to be bought and others allocated for free by the EU - known as free allocation. Over time, the system expanded to cover more industries and incorporated updated market mechanisms. This market mechanism created a "carbon market," allowing actors within the economy to buy and sell carbon credits, establishing a market-based system for regulating carbon emissions. Although this mechanism was intended to stimulate a transition to a greener society, risks of firms relocating production to unregulated regions due to increased production prices, also known as carbon leakage, became more prominent in political discussions (Commission, 2020). Climate goals are at risk, along with the EU's competitiveness, because emissions are being displaced rather than reduced, and prices within the EU are becoming relatively higher (European Comission, n.d.-a).

The discussion around carbon leakage emerged from extensive research and modelling showing that economic actors would leave the EU due to a lack of competitiveness (Cameron and Baudry, 2023). However, empirical evidence during the implementation of ETS showed no carbon leakage occurring as the policy progressed (Verde, 2020). This contradiction between modelling and reality likely stemmed from the use of data from the first two phases of ETS (2005-2012), characterized by low carbon prices and widespread free allocation (Naegele and Zaklan, 2019). The EU developed an import tax on goods that was proportional to their carbon footprint, known as CBAM, to address this modelled carbon leakage (European Union, 2023). CBAM adds an import tax proportional to the emissions of products produced outside of the EU. This disincentivizes producers from moving operations abroad, where it is cheaper, and then importing the product. Doing this should also protect the competitiveness of the EU (Commission, 2020). After 9 years of drafting, the CBAM policy was completed in 2020. It was finally adopted in May 2023 and was implemented in October 2023 starting with high-risk sectors - sectors with a high chance of moving operations - and will be expanded to all sectors by 2030 (European Union, 2023).

As CBAM is currently being implemented, there is no empirical data available to verify the models used in its development. The literature on CBAM effectiveness remains uncertain, with a wide range of estimates, and the assumptions used in models have significant effects. This begins to reveal an academic knowledge gap. In further uncovering and motivating the academic knowledge gap, it is crucial to reiterate the limitations in existing research on carbon pricing mechanisms and their effects, particularly with CBAM. Previous studies on carbon pricing and carbon leakage have often relied on outdated data, primarily from periods of low carbon prices and extensive free allocation, leading to uncertainties in modelling outcomes (Perdana and Vielle, 2023). The implementation of CBAM introduces a new dimension to this, yet empirical evidence is lacking to validate existing models (Kuusi et al., 2020). This paper therefore aims to quantify the price effects of carbon policy in the EU by calculating the change in production costs and competitiveness per country and per sector which can be formulated in the main research question:

What are the price effects of carbon pricing and CBAM on the EU?

To answer this question effectively it was necessary to incorporate more recent and granular data into research methodologies, such as Input-Output modelling, to better understand the impacts of carbon policies on production costs and competitiveness (Schotten et al., 2021). By filling this knowledge gap, this research aims to provide policymakers with clearer insights into the implications of carbon pricing and CBAM, facilitating more informed decision-making processes.

The goal of this thesis is to provide clarity and quantifiable data by calculating the impact of carbon policy with, and without, CBAM on production costs and competitiveness. It will do this by using Input-Output modelling, with up-to-date data, to uncover the direct and indirect effects these policies have within the EU economy. Tax will first be applied on the value added and by doing this, production cost and competitiveness per sector and per country will be calculated in different scenarios. After this, the novel method of tax on intermediate sales will be used and compared to the initial results along with a sensitivity analysis. By first providing updated results using more recent and detailed data with the commonly used tax on value-added method and then comparing that to the novel tax on intermediate sales method, this thesis contributes to scientific literature in two distinct ways. This comparison, along with a sensitivity analysis, will offer valuable insights to help inform better policy decisions.

This thesis is set up as follows. First of all, in chapter two, a reviews existing literature to understand the foundations of carbon policy and what the state of research currently is. Based on this, the academic knowledge gap will be uncovered and this leads to the main research question. In chapter three, the methodology is outlined along with the explanation of the data and subsequently, the results & discussion are presented in chapter four.

# 2 | Academic knowledge gap & Main research question

This chapter will focus on providing a theoretical background for carbon policy in the EU and identifying the main concepts relevant to CBAM in scientific literature. Furthermore, the conclusions of the literature will be discussed and recommendations will be used to bring to light what the academic knowledge gap is culminating in the main research question.

## 2.1. Literature review

In this section, the most pertinent research will be reviewed starting with background theory and then going onto types of modelling, the results of modelling, and the potential reasons for discrepancies with empirical data. Lastly, broader literature will briefly be reviewed about administrative, and legal aspects as well as how Sustainable Energy Technology fits into this.

### 2.1.1. Theoretical background

#### Carbon leakage

Carbon leakage - the displacement of production to unregulated areas - is the fundamental negative drawback in carbon taxation and therefore warrants further analysis. Hoel (1991) did the first research on carbon leakage and concluded that if one country chooses to unilaterally implement a carbon policy while another does not, then emissions will simply be shifted from one country to another and the total emissions will not change. This shift will happen when the cost increase for a firm due to a carbon tax exceeds the cost of relocation (Cameron and Baudry, 2023).

Three types of carbon leakage can be described, which occur through several different channels. These are namely the competition channel, energy channel, and the innovation channel (Cameron and Baudry, 2023).

The policy debate over the last years has generally centred around the competition channel. The general structure of the competition channel is illustrated in Figure 2.1. This channel visually demonstrates how climate policy theoretically leads to higher production costs, which in turn reduces competitiveness. This lack of competitiveness results in the transfer of production to unregulated areas and finally leads to higher emissions.

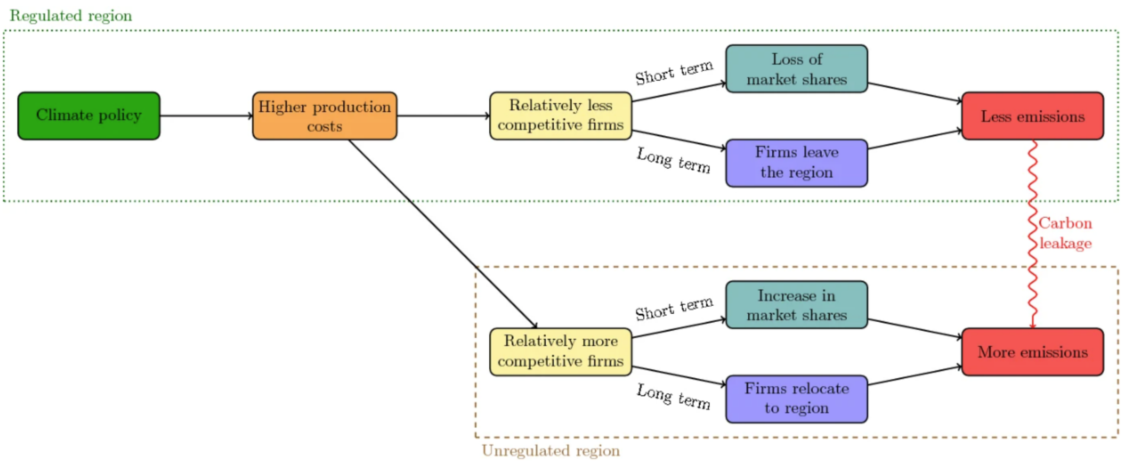


Figure 2.1: Competition channel (Cameron and Baudry, 2023)

The energy channel, on the other hand, describes the impact of higher production prices on consumers, resulting in decreased energy demand within regulated regions. This, in turn, leads to lower global prices, increasing energy demand in unregulated regions and consequently more emissions. The energy channel is visualised in Appendix C.

Lastly, the innovation channel represents the process by which climate policy increases production costs, thereby stimulating innovation in cleaner technologies. If this technology leaks out to unregulated areas, total emissions are reduced. This represents the only positive form of leakage. The innovation channel is visualised in Appendix C.

When looking at carbon leakage in the form of shifting production to unregulated areas the competition channel is the most consequential out of the three channels.

#### SECTORAL LEAKAGE

Apart from regional leakage, sectoral leakage can occur. This takes place within an existing region, economy, and production structure. This happens when carbon taxes on heavy industry increase production costs, shifting demand to other sectors and potentially increasing their emissions (Zhang and Zhang, 2017).

#### PRODUCTION COSTS & COMPETITIVENESS

Fundamentally, there are two interrelated factors in carbon leakage namely, production costs & competitiveness. It is important to define these factors. Carbone and Rivers (2017) discusses that competitiveness in economics is an ambiguous topic. Fagerberg (1996) discusses how the term has been a topic of debate among economists as it is always a comparative measure and the scope of what it defines varies. It could be related to a country's ability to create a high quality of life for its population by doing better than another country, or it could be about export prices. Technology and innovation are also mentioned as major factors in long-term competitiveness, with R&D being important across many industries. R&D brings additional benefits to other sectors, making public support crucial, especially for smaller countries with limited markets. Lastly, the argument is made that sharing technology between countries can promote global growth and improve welfare.

To simplify competitiveness into a quantifiable metric, it will be defined as follows: the price variations in local production compared to price variations in the import prices into the EU (Schotten et al., 2021). Production costs, on the other hand, can be defined as the sum of the costs of raw materials, labour, and capital needed to process these raw materials into the final product, along with the taxes that need to be paid. Rising production costs can lead to carbon leakage, as it becomes cheaper to produce in unregulated areas, resulting in a competitive disadvantage for the EU compared to regions outside the EU (International Monetary Fund, 2021). By understanding these key parameters, the impact of carbon tax directly on production costs & competitiveness should be investigated further.

#### CARBON BORDER ADJUSTMENT MECHANISM

The Carbon Border Adjustment Mechanism (CBAM) works by taxing the embodied emissions of a good upon entry to a regulated area, in this case, the EU. The embodied emissions include both direct and indirect emissions of a product. A tax must be paid on this, which is the same as the tax rate used within the EU. This ensures that it is not possible to sell to the EU market and avoid carbon taxes by simply shifting production abroad and importing it into the EU (Commission, 2020).

The embodied emissions considered for CBAM include all Scope 1 and certain Scope 2 emissions. Scope 1 emissions refer to direct emissions generated from assets owned or controlled by the producer. Scope 2 emissions are those associated with energy sources used in production, such as electricity or steam (DG Taxation and Customs Union, 2024). In the current transitory phase until 2025 all scope 1 emissions are taken into account for CBAM as well as scope 2 emissions for fertilizer, cement & electricity. From 2025 the inclusion of scope 2 emissions is likely to be expanded to more CBAM sectors (Commission, 2023). Scope 3 emissions include things like transportation, employee commuting & buildings and these are currently not included in CBAM.

In practice, when goods are imported into the EU, importers must declare and pay for the embedded emissions. This is done by purchasing certificates which correspond to the EU ETS price for carbon and, upon import, surrendering the proportional number of certificates to emissions. If a carbon tax has already been paid in the country of origin, this can be subtracted from the amount needing to be paid (DG Taxation and Customs Union, 2024).

Furthermore, there is currently a distinction between which downstream products are subject to CBAM. For example, CBAM applies to aluminium bolts and nuts but not to car doors in the current transition stage (Carbon-Chain, 2024). There are lots of variations in which exact products are included and not included and the list of what is included will also expand over the next decade.

Carbon intensity

Carbon intensity is another commonly used metric in literature. Carbon intensity refers to the carbon dioxide emissions per specified metric, often some output amount in financial or quantity terms (Wang et al., 2018). This can be used to describe the difference between sectors with a lot of emissions per output and relatively cleaner ones producing less emissions for the same output.

### 2.1.2. Existing literature

To gain a better understanding of the state of carbon leakage, increases in production prices and changes in competitiveness, a review of recent studies was done. First of all the types of modelling are outlined, the results are analysed and then this is compared to literature which looks at empirical evidence.

Types of modelling

There are two main methods commonly used to evaluate increases in production costs, carbon leakage and competitiveness: General Equilibrium Modelling and Input-Output (IO) modelling. General Equilibrium Models describe the structure and behaviour of economies and how they would respond to changes by finding a new equilibrium for supply and demand. They account for dynamic and changing factors, such as the behaviours of firms, providing a more comprehensive economic view (Böhringer et al., 2003). However, they are more complex, computationally expensive, and highly sensitive to assumptions. In contrast, Input-Output modelling uses fixed economic data which describes the relationship between producing and buying sectors and assumes that the ratios between inputs and outputs are constant. Input-output analysis is better suited for short-term analyses with fixed economic structures. While simpler and less computationally demanding, it is more limited in its ability to model long-term changes and so only gives insight into short-term responses (Miller and Blair, 2009). Within IO modelling, two methods are seen, cost-push and demand-pull. Demand-pull describes how output quantities vary with changes in demand, whereas cost-push shows how prices change when a change is made in value-added. Cost-push is the relevant one when looking at carbon taxation and will be focussed on moving forward.

Schotten et al. (2021) outlines two methods of taxation; tax on value-added and tax on intermediate sales. Tax on value added is a common and simple method of taxation that can be seen on many products in day-to-day life, more commonly known as VAT. This ensures that the tax is applied to the emissions associated with the value added by each sector to a certain good or product. Tax on value added is the main method used in literature. The tax on intermediate sales adds a tax to the gross value of the product at every stage of the supply chain. This may give insights into the knock-on effects of taxes early in the supply chain, although there is limited research on this method. Tax on value added is frequently chosen and the reason is often not motivated. One potential reason found in the literature is the risk of cascading taxes when applying tax on intermediate sales which could cause large overestimations of how much tax should be paid (Shome, 1995).

Results

Starting with literature on carbon leakage, Branger and Quirion (2014) reviewed 25 studies in a meta-analysis examining a total of 310 estimates of leakage rates. The studies reviewed were predominantly general equilibrium models with some models using similar techniques but focusing on specific sectors. It concluded that production costs will increase more in regulated areas than non-regulated areas and that current models estimate carbon leakage rates of heavy industry to be between 5-25%, stressing that carbon leakage poses a serious threat to the effectiveness of EU ETS.

Furthermore, a systematic review of 54 studies using computational equilibrium models showed that with a unilateral carbon policy designed to reduce emissions by 20%, the production and export in energy-intensive sectors fall by 5-7% due to rising production costs and losses in export competitiveness (Carbone and Rivers, 2017). Here again, it is seen that competitiveness and production costs are closely related.

Looking further at the impact of a carbon tax and CBAM on production costs Schotten et al. (2021) used Input-Output modelling to understand the impacts, on the EU specifically. They employ the tax on value-added method within input-output modelling. A notable rise in production costs across the EU and in all sectors can be seen in Figure 2.2 and Figure 2.3 respectively. The method of input-output modelling gives an excellent overview of the impact per country and sector by considering trade between them.

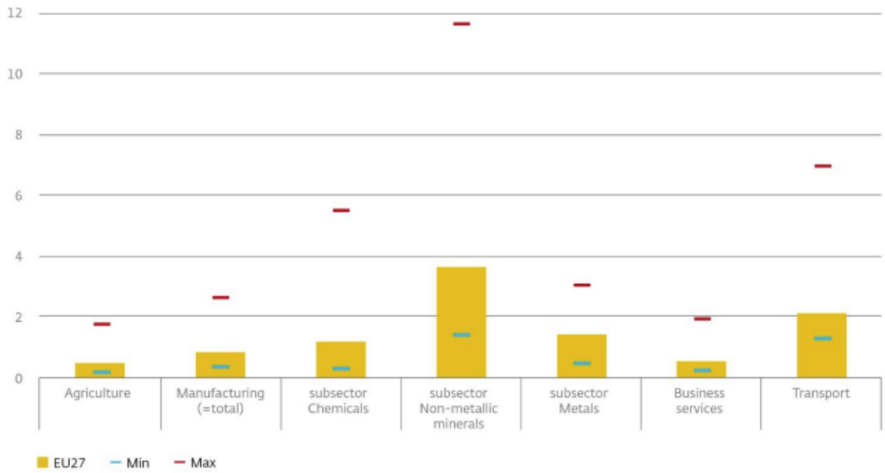


Figure 2.2: Percentage change in production costs per sector using a 50 euro carbon tax (Schotten et al., 2021)

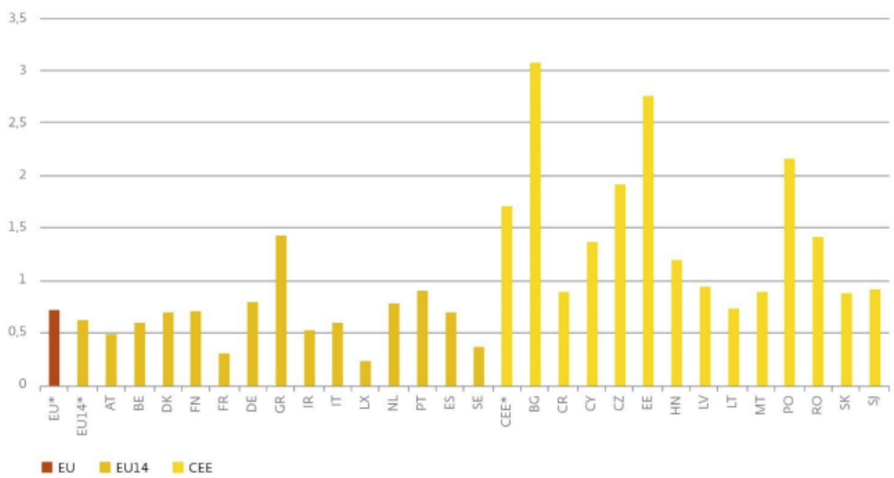


Figure 2.3: Percentage change in production costs per country using a 50 euro carbon tax (Schotten et al., 2021)

This study developed an input-output model based on the EU's production structure to analyze different carbon prices and CBAM implementations. The findings show that while carbon prices raise production costs and lower competitiveness, CBAM helps level the playing field by making imports more expensive, which offsets the cost differences for domestic EU producers (Schotten et al., 2021).

The effectiveness of CBAM has also been modelled with general equilibrium methods and has shown that carbon leakage could be brought down from around 25% to 5% with the implementation of CBAM (Branger and Quirion, 2014, Mörsdorf, 2022). Perdana and Vielle (2023) come to similar conclusions on the effectiveness of CBAM and reiterates that for full effectiveness CBAM should be applied to embodied emissions and heavy industry, expansion beyond this may have limited upside potential.

After reviewing literature it becomes clear that General equilibrium models are predominantly used to explore production costs, competitiveness and carbon leakage and that less is done with input-output modelling. Looking at the limitations and recommendations of existing literature a few academic knowledge gaps begin to appear. First of all, the high impact of assumptions in general equilibrium analysis is frequently named. Value can be added to the scientific community by using other methods, such as input-output methods, to converge on more accurate conclusions on the effectiveness of CBAM (Perdana and Vielle, 2023). Verde (2020) identifies a crucial knowledge gap in understanding the sector-specific effects of carbon policy, emphasizing the need for further investigation in this area. A powerful tool for addressing this gap is Input-Output modelling, which can provide valuable insights into the interdependencies within the EU economy, particularly by analyzing intermediate input linkages and their broader impact on different sectors.

#### EMPIRICAL EVIDENCE

When comparing both modelling methods to empirical evidence on the impact of carbon tax on production costs, carbon leakage and competitiveness differences are seen. The effects seen since the inception of carbon tax are generally smaller than those modelled (Dechezleprêtre and Sato, 2017). This is largely with respect to the magnitude of carbon leakage, this is happening less than expected. Systematic reviews of empirical data have shown that there is no evidence of carbon leakage actually occurring (Verde, 2020). Even when looking at the most likely actors to move production, namely multi-nationals, there has been no relocation of production (Dechezleprêtre et al., 2022).

When searching for empirical evidence on CBAM limited literature is available. This is because of the implementation of CBAM occurring in October of 2023, there is no data on what the real effects are compared to modelled ones. Due to the lack of empirical data, there is a strong need for further modelling to enhance economic insights into these policies (Kuusi et al., 2020).

#### REASONS FOR DISCREPANCIES

There are several reasons for discrepancies between empirical data, or lack thereof, and the modelling studies which have been performed. Starting with a common theme in the literature; the rapidly evolving nature of carbon policy and the CBAM. This highlights the need for continuous research with updated data to assess their effects within and outside the EU (Naomi Newman, 2022). Many empirical studies focus on data from the first two phases of the EU ETS (2005-2012), a period marked by relatively low carbon prices and significant free allocation of carbon credits by the EU (Naegele and Zaklan, 2019).

To reduce the discrepancies between literature and reality, the literature recommends that more studies be done that utilize data from recent phases, where carbon prices are higher and free allocations have decreased. Discrepancies between modelling and real-world outcomes stem from several factors. Firstly, computational general equilibrium models are highly assumption-dependent, so further research using alternative techniques, such as Input-Output modelling, could help verify results on production costs and competitiveness (Carbone and Rivers, 2017). Secondly, as highlighted earlier, newer data and sector-specific analysis are essential for more accurate results as sector-specific behaviour may vary greatly from the average impacts (Verde, 2020, Naegele and Zaklan, 2019). This is reinforced by zooming in on input-output modelling studies that show existing data lacks the granularity needed to fully capture sectoral differences. It suggests using more detailed databases to improve the accuracy of sectoral impact assessments (Schotten et al., 2021).

### 2.1.3. STIMULATING SUSTAINABLE ENERGY TECHNOLOGY INNOVATION

There is evidence to show that innovation in Sustainable Energy Technology is stimulated through carbon policy. Theory suggests this can be linked to the aforementioned innovation channel, which shows how carbon policy encourages investment in carbon-abating technologies (Cameron and Baudry, 2023). However, it is unclear whether the benefits of this innovation outweigh any downsides that environmental policies may have (Dechezleprêtre and Sato, 2017). One clear example of a carbon tax implementation that reduced emissions while fostering innovation in sustainable technologies and GDP growth is Sweden. In 1991, Sweden implemented a carbon tax of 139 euros per tonne, and the country saw a 16% decrease in emissions from 2000-2012 while experiencing 30% GDP growth (Newman, 2021). Other systematic reviews argue that there is limited empirical evidence to show that carbon taxation alone triggers investment in innovation, although it has been effective in combination with other measures such as subsidies and investment in infrastructure (Lilliestam et al., 2021). Empirical evidence is limited, and further research could contribute to greater confidence on the matter.

### 2.1.4. ADMINISTRATIVE & LEGAL COMPONENTS

There are still concerns regarding CBAM's compliance with World Trade Organization (WTO) regulations. Key issues include fears that CBAM could trigger trade wars, as countries may prioritize their own interests over promoting free trade. Additionally, questions remain about the practical aspects of CBAM's rollout and implementation, which could affect its acceptance and overall effectiveness (Kuusi et al., 2020).

## 2.2. ACADEMIC KNOWLEDGE GAP

Several academic knowledge gaps have appeared which open up opportunities for state-of-the-art research, these will briefly be recapped. Firstly, as previously mentioned, throughout the literature, there is simply a lack of research using up-to-date data from time periods where carbon prices were higher, free allocation was used less, and carbon policy was generally stricter (Naegele and Zaklan, 2019). Additionally, studies argue that research needs to be developed further with databases of higher granularity for more specific data (Schotten et al., 2021). Thirdly, from systematic reviews of literature, there is a strong recommendation to develop more sector-specific information on the short-term impact of CBAM (Verde, 2020). One reason for variation in modelling with general equilibrium models is their heavy reliance on assumptions. Using other models to verify and contribute to existing research can increase confidence in projections (Carbone and Rivers, 2017).

Pursuing research that uses IO instead of computational equilibrium modelling with newer data of higher granularity, as well as shedding light on the sector-specific impacts and linkages of the European production structure, would address the aforementioned academic knowledge gaps. This thesis will contribute to state-of-the-art scientific literature in two distinct ways.

The first contribution is an iteration using input-output analysis, tax on value-added and newer, more granular data to assess price effects on the EU. This builds on the study by Schotten et al. (2021) with De Nederlansche Bank, which used 2015 data, and will shed more light on sector-specific impacts than prior research. It provides more confidence in the methodology used and the results by increasing the research volume employing this method. The second distinct contribution is by implementing and comparing a relatively unexplored method in IO modelling for a carbon tax— a tax on intermediate sales. This will be one of the first studies, if not the first, to compare these methods in this context and to compare the results to the widely used method of tax on value added. It will shed light on the top-level mechanics of this methodology and recommend areas for further research regarding the tax on intermediate sales method.

## 2.3. MAIN RESEARCH QUESTION

Based on evaluating the relevant literature and looking at the academic knowledge gaps that exist, it has been chosen to focus on the underlying causes of carbon leakage: production cost and competitiveness. This is the main reason carbon leakage can occur and also has knock-on effects for the rest of the economy. This leads to the main research question.

What are the price effects of carbon pricing and CBAM on the EU?

The value of using input-output analysis is that it allows analysis of policies based on current economic structures in a computationally simple way. This allows for evaluating the short-term economic impacts of alternative policy scenarios.

## 2.4. SUB-RESEARCH QUESTIONS

The main research question is broken down into 5 sub-research questions.

### 2.4.1. SUB-RESEARCH QUESTION 1

*How can the cost-push input-output price model estimate the impacts of carbon pricing and CBAM on production costs and competitiveness? What data sources are needed, and what are the benefits and limitations of using a cost-push input-output price model for this purpose?*

### 2.4.2. SUB-RESEARCH QUESTION 2

*What is the impact of carbon pricing on production costs and competitiveness per sector and per country within the EU?*

### 2.4.3. SUB-RESEARCH QUESTION 3

*What is the impact of the addition of CBAM on production costs and competitiveness per sector and per country within the EU?*

### 2.4.4. SUB-RESEARCH QUESTION 4

*What is the effect of applying tax using the intermediate sales method, how do the results compare and what are potential reasons for differences?*

### 2.4.5. SUB-RESEARCH QUESTION 5

*What is the net effect of a combination of carbon pricing on the EU & its trading partners?*

# 3 | Methodology

## 3.1. Foundations of Input-Output theory

The purpose of this thesis is to analyze the price effects of carbon policy. To establish a common understanding of the theory used, input-output (IO) theory will be explained, as well as how it can be used to evaluate the price effects of carbon policy.

IO analysis uses a detailed matrix that represents the flow of goods and services between various sectors within an economy and between economies. This matrix is essentially a table where each row represents the output of a sector, while each column represents the inputs used by a sector. For instance, the agriculture row shows how much of its produce is supplied to industries like food manufacturing and textiles. The agriculture column, in turn, shows the inputs it receives from sectors such as fertilizer production, machinery, and transportation. This layout allows for a clear analysis of how different parts of the economy depend on each other.

IO analysis is a powerful tool for modelling different scenarios and evaluating the direct and indirect impacts of various policies. For example, if a new policy significantly boosts demand for electric vehicles, IO analysis can model the short-term impact on related sectors such as battery manufacturing, lithium mining, and the energy sector. It not only shows direct effects but also indirect effects, such as how a tax on steel could impact downstream sectors like transportation. This provides policymakers with insights into how policies affect prices and output, and what the potential effects of these changes might be.

First, the data structure will be broken down and explained. From this, the mathematical model will be developed and explained, showing how it can be used to measure the price impacts of carbon policy.

### 3.1.1. Data

It was concluded in the literature review that more recent data with higher granularity would contribute to scientific literature. For this reason, the FIGARO database is chosen. FIGARO stands for "Full International and Global Accounts for Research in Input-Output Analysis" and is based on data from EU member states, the OECD, and the United Nations (eurostat, 2021). The FIGARO database describes the flows between the 27 EU countries, the 18 main trading partners of the EU, and an aggregated "rest of world" area. An overview is given in Table 3.1.

These geographic regions are broken down into 21 industries which can be seen in Table 3.2. These sectors are broken down into 64 industries which can be found in appendix section A.1.

Table 3.1: FIGARO Countries

| EU Country | Code |
|---|---|
| Austria | AT |
| Belgium | BE |
| Bulgaria | BG |
| Croatia | HR |
| Cyprus | CY |
| Czechia | CZ |
| Denmark | DK |
| Estonia | EE |
| Finland | FI |
| France | FR |
| Germany | DE |
| Greece | GR |
| Hungary | HU |
| Ireland | IE |
| Italy | IT |
| Latvia | LV |
| Lithuania | LT |
| Luxembourg | LU |
| Malta | MT |
| Netherlands | NL |
| Poland | PL |
| Portugal | PT |
| Romania | RO |
| Slovakia | SK |
| Slovenia | SI |
| Spain | ES |
| Sweden | SE |

| Trading partner | Code |
|---|---|
| Argentina | AR |
| Australia | AU |
| Brazil | BR |
| Canada | CA |
| China | CN |
| India | IN |
| Indonesia | ID |
| Japan | JP |
| Mexico | MX |
| Norway | NO |
| Russia | RU |
| Saudi Arabia | SA |
| South Africa | ZA |
| South Korea | KR |
| Switzerland | CH |
| Türkiye | TR |
| United Kingdom | UK |
| United States | US |
| Rest of World | FIGW1 |

Table 3.2: Sector

| Industry Code | Sector |
|---|---|
| A | Agriculture, forestry and fishing |
| B | Mining and quarrying |
| C | Manufacturing |
| D | Electricity, gas, steam and air conditioning supply |
| E | Water supply; sewerage; waste management and remediation activities |
| F | Construction |
| G | Wholesale and retail trade; repair of motor vehicles and motorcycles |
| H | Transporting and storage |
| I | Accommodation and food service activities |
| J | Information and communication |
| K | Financial and insurance activities |
| L | Real estate activities |
| M | Professional, scientific and technical activities |
| N | Administrative and support service activities |
| O | Public administration and defence; compulsory social security |
| P | Education |
| Q | Human health and social work activities |
| R | Arts, entertainment and recreation |
| S | Other services activities |
| T | Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use |
| U | Activities of extraterritorial organisations and bodies |

In line with standard practice, the FIGARO data is given in matrix form which can be broken down into several sub-matrices. Figure 3.1 gives a simplified picture of how the data is organised. On the left are all of the input sectors into the economy, otherwise known as the selling sectors. These sectors are the indices for the rows of the matrix. On top of the matrix, these same sectors are placed once again as the indices for the buying sectors.

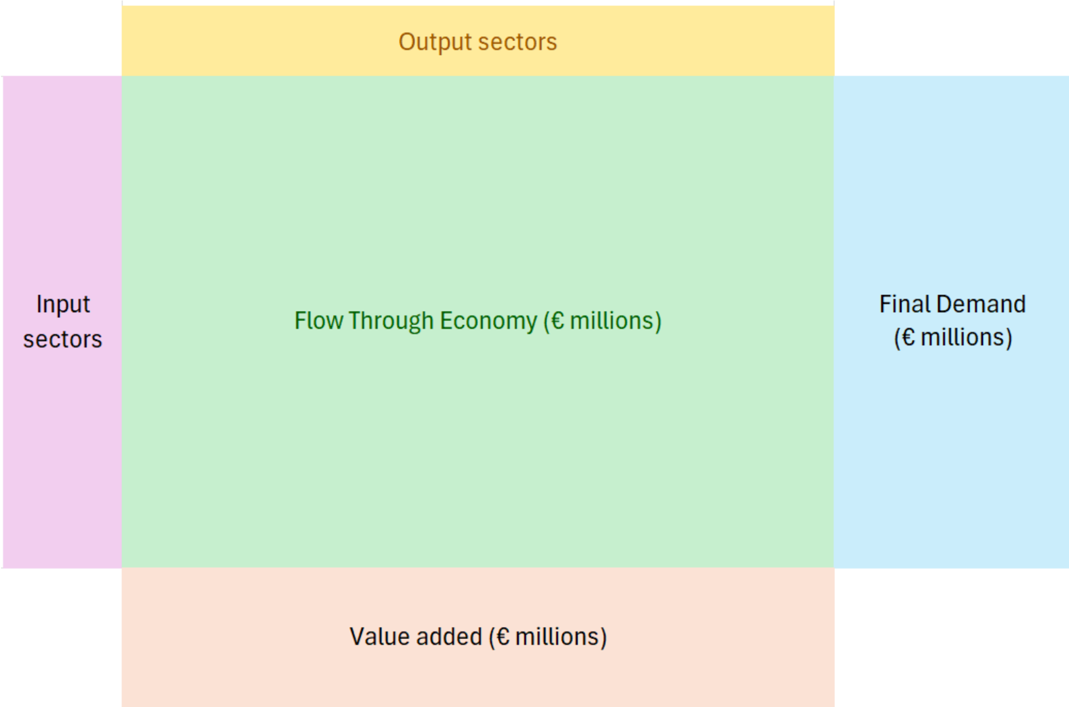


Figure 3.1: Simplified structure of the FIGARO database

The green section in Figure 3.1 is the Z matrix. This represents all of the intermediate sales from one industry in one country to all other industries and countries. The blue section is the final demand in the economy for a specific industry from a specific country. The orange section is the value added comprised of things such as wages and taxes. These will be explained further.

An example of how the data would appear once processed can be seen in Table 3.3. Here C represents a country and S represents a sector. This is a simplified model and all components have monetary units.

Table 3.3: Example Table of FIGARO data

| | **Sectors** | | | **Final demand** |
|---|---|---|---|---|
| **Sectors** | 1 | 2 | 3 | |
| 1 | $z_{11}$ | $z_{12}$ | $z_{13}$ | $f_1$ |
| 2 | $z_{21}$ | $z_{22}$ | $z_{23}$ | $f_2$ |
| 3 | $z_{31}$ | $z_{32}$ | $z_{33}$ | $f_3$ |
| $v_j$ | $v_1$ | $v_2$ | $v_3$ | |

Each Z value in the table represents the financial value transferred starting from the origin country and sector on the left of the table to the country of destination on the top of the table. In addition to the Z matrix, which will be explained further, there is also the final demand and the value added. The final demand can be broken down into several extra categories ranging from government consumption to capital formation. For a detailed breakdown of the final demand please see appendix section A.2. Similarly, value added can be broken into categories ranging from employee compensation to taxes. For a detailed breakdown of the value added please see appendix section A.3.

The data was broken down into useful sub-matrices for further processing. The sub-matrices of value added (V), final demand (f) and intermediate sales (Z) are essential for further processing which will be explained in the next section.

### 3.1.2. ASSUMPTIONS

THEORETICAL ASSUMPTIONS

The assumptions are largely based on the theory on input-output analysis in the book "Input-Output Analysis: Foundations and Extensions" (Miller and Blair, 2009). There are several assumptions with input-output analysis. Firstly, no technical substitution in the economy: the efficiency at which something is produced will not vary within the time frame that is being looked at. This means that technology and processes do not have time to react to price changes. This allows for modelling the immediate effects, but not the long-term effects, as technology and processes will change in response to changing economic conditions. Secondly, fixed input-output coefficients: flows between industry $i$ and industry $j$ are completely defined by the output of sector $j$. Therefore, increasing the input without increasing the output has no effect. Thirdly, economies of scale are ignored. This is because the technical coefficients remain fixed and there is no change in these with changing production levels within the model. This means the system works on a constant returns to scale (Miller and Blair, 2009).

Furthermore, the model does not account for input constraints. This means it does not consider supply chain shortages, so significant changes in input for a certain sector should be taken into account if such constraints are relevant. Within a sector, no product differentiation is assumed with FIGARO data. For example, there is no differentiation between a train or a car, or a Ford or a Mercedes in the land transport sector. Lastly, static analysis. IO analysis is a static analysis; it does not include dynamic changes over time due to technological advancements, changes in consumer preferences, or economic growth.

MODEL SPECIFIC ASSUMPTIONS

Throughout the development of the model columns with zero value added and zero total output were manually set to zero when mathematical operations were done. This was due to these columns causing errors due to the division by zero sometimes even though these sectors due not contribute to the economy. This assumption comes because of the real-world data used; in classic IO theory, only sectors that participate in the economy are considered. In the FIGARO database, all sectors were presented yet some did not partake in the economy.

Furthermore, some assumptions are made as to what the next iterations of ETS will cover. For example, ETS is being updated to cover more sectors, although it will not in the next years cover agricultural activities. In this thesis, the assumption is made that ETS will cover all sectors in future iterations. This is to provide a complete overview of what the impacts of carbon taxation would be if applied to all EU sectors. If it is not applied to some sectors, then this thesis simply provides the upper bound and an overestimation. Lastly, normally credits are purchased beforehand as a "permission to emit." In this model, a carbon tax is placed proportional to emissions. This means that the mechanism for paying for emissions is modelled differently, however, at this current stage, the outcome should be the same. It then assumes that there are enough credits to be purchased for emissions at the moment. These credits will reduce in number over the next 10 years, and firms will then be forced to emit less.

### 3.1.3. CORE BUILDING BLOCKS

The theoretical framework described is based strongly on the explanations given in the textbook "Input-Output Analysis: Foundations & Extensions" (Miller and Blair, 2009). So starting with a specific sector, the fundamental building block is the flow of sectors to one another. By looking at one sector Equation 3.1 describes how the output of that sector is defined in IO analysis.

$$\text{Total output of a sector} = \begin{bmatrix} \text{What the sector sells to} \\ \text{other sectors} \end{bmatrix} + \begin{bmatrix} \text{What the sector sells} \\ \text{as a final product} \end{bmatrix} \tag{3.1}$$

Mathematically defining this logic it can be said that Equation 3.2 describes the general flows within the economy. The total output $x_i$ is equal to the sum flows from sector i to all other sectors plus the final demand for the product $x_i$ in the economy.

$$x_i = \sum_{j=1}^{n} z_{ij} + f_i \tag{3.2}$$

where

- $x_i$ - Total output of sector i
- $z_{ij}$ - Flow from sector i to a sector j
- $f_i$ - The final demand in the economy for the output of sector i

This can be generalised into a matrix form for all sectors:

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} \tag{3.3}$$

Which can be expanded to be

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} Z_{11} & \dots & Z_{1n} \\ \vdots & \ddots & \vdots \\ Z_{n1} & \dots & Z_{nn} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} + \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \tag{3.4}$$

This forms the basis of IO analysis. For a more detailed derivation please see appendix section B.1.

### 3.1.4. MATHEMATICAL PROCESSING AND ANALYSIS OF IO DATA

The first processing step which can be applied to the input-output data is calculating the technical coefficients of the economy, due to the importance of these equations, this derivation is placed centrally and not in the appendix. Technical coefficients, which are fixed, represent the amount of output which is bought from another sector compared to the final output of the producing sector. In the case of the aircraft industry, the technical coefficient which represents the flow from the aluminium industry to the aerospace industry is defined in Equation 3.5 (Miller and Blair, 2009). It is the value of aluminium bought by the aircraft producer divided by the total value of the aircraft.

$$a_{ij} = \frac{z_{ij}}{x_j} = \frac{\text{value of aluminium bought by aircraft producers last year}}{\text{value of aircraft production last year}} \tag{3.5}$$

This can be carried out for every single element in the matrix Z which allows for a technical coefficient matrix A to be calculated.

$$\mathbf{A} = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix}, \tag{3.6}$$

The Leontief inverse is introduced. This is a constant matrix and can be defined as:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{3.7}$$

This yields the central Equation 3.8

$$\mathbf{x} = \mathbf{L} \cdot \mathbf{f} \tag{3.8}$$

For the derivation please see appendix section B.2. This Leontief matrix is the foundation of IO analysis. Through a series of mathematical operations, it can be calculated from the IO data. The Leontief inverse is a constant matrix which represents the flows within a whole economy as a function of fixed technical coefficients. This can be used as a basis for further analysis and evaluation of certain changes to inputs or outputs within the economy. Please note that this model can be evaluated in terms of quantity or price, but for the analysis done in this research, price was used as the unit.

### 3.1.5. VERIFICATION

TESTING THE BASE DATA

The model was verified, confirming that the core aspects were correct and usable for further analysis. This was done by multiplying the Leontief inverse calculated in Equation 3.7 with the final demand vector. The output should be equal to the total output of every sector, which it was. Therefore, all steps were followed correctly.

HAWKINS-SIMON CONDITION

The Hawkins-Simon condition ensures that an economy is stable and can meet its production requirements without unrealistic or unsustainable growth occurring in any sector. It also gives insight into the balance between sectors and ensures that no sector's growth will cause a shortage or instability. It ensures that all sectors can maintain non-negative outputs to make the system work, if a production structure is such that a sector has to provide negative output to ensure that the system works, this is no longer a realistic, sustainable or stable economy and should not be used for analysis as it will not give accurate results. Simply put, all final demands and outputs must be zero or greater than zero to be realistic. This can be checked using the equations below by ensuring that the largest eigenvalue of A does not one. This is applied in the model as an extra verification step to ensure it stays within acceptable bounds.

$$\det(\mathbf{I} - \mathbf{A}) > 0 \quad \text{so} \quad \lambda_{\text{max}} < 1$$

## 3.2. APPLICATION OF FOUNDATIONS - COST PUSH

The Leontief matrix can be used in several different ways to analyse the impact on the economy. This can be a change in demand or input prices. Changes in final demand change how much output every sector has. However, to look at price effects due to carbon pricing, changes in input prices are more interesting. Changes in input prices, such as taxes or employee wages, have an impact on the production prices of items in the economy. To analyse this the cost-push method is used.

This cost-push model focuses on how changes in value-added within an industry can influence final product prices. Equation 3.10 captures this relationship in mathematical terms and Equation 3.9 explains the logic. Here the price is the ratio of inputs and outputs needed to produce everything in the economy multiplied by the monetary value every unit of output produces, broken down into wages, taxes and so on. The ratio of inputs and outputs is fixed. If taxes on a certain product increase, the value added per unit output would change, causing the product's price to also change, resulting in price changes. This is the essence of the cost-push model, changing the value added to the economy causes changes in the prices and the ripple effect through the economy can be measured. For example, suppose the wages of steelworkers are increased. In that case, this increases the value added for the steel industry, and would make the price per unit of steel higher, and would have a knock-on effect for every industry that uses steel in their product, like the construction sector for example.

Here, $\mathbf{P}$ represents the final price, $\mathbf{L}'$ reflects the weighted average cost of inputs from other industries. This transposed Leontief matrix described the fixed relationships between inputs and outputs in the economy and was calculated earlier. $\mathbf{V_c}$ represents the value added per unit of output of a particular sector. For a more detailed derivation of Equation 3.10 please see appendix section B.3.

$$\text{Price factor} = \left[ \begin{array}{c} \text{Fixed ratios of inputs} \\ \text{and outputs in the economy} \end{array} \right] \cdot \left[ \begin{array}{c} \text{value added} \\ \text{of one unit of output} \end{array} \right] \tag{3.9}$$

in mathematical terms

$$\mathbf{P} = \mathbf{L}' \cdot \mathbf{v_c} \tag{3.10}$$

where

$$\mathbf{v_c} = \begin{bmatrix} v_{c_1} \\ \vdots \\ v_{c_n} \end{bmatrix} \quad \text{and} \quad v_{c_j} = \frac{v_j}{x_j} \tag{3.11}$$

This can now be used to understand the price effects of changes in value added. For example, if value-added changes, due to wages increasing in one sector for example, or taxes increasing, this equation yields a price factor. A price factor of 1.2 would indicate a 20% increase.

## 3.3. INPUT-OUTPUT THEORY FOR CARBON PRICING

IO analysis was used to analyse the effects of carbon pricing. This was done based on carbon emissions. The FIGARO database has corresponding carbon emissions for every single sector. This forms the basis for seeing how the economy would react to a carbon tax.

### 3.3.1. CARBON TAX

In this model, carbon tax was calculated by choosing a carbon tax per tonne of $CO_2$. The absolute amount of tax paid per sector $t_j$ was equal to the tax rate $t_r$ multiplied by the emissions by that particular sector in that country. This is described in Equation 3.12 and mathematically described in Equation 3.13.

$$\text{Tax revenue} = \begin{bmatrix} \text{Tax rate per tonne of} \\ \text{emitted } CO_2 \end{bmatrix} \cdot \begin{bmatrix} \text{Tonnes of } CO_2 \text{ emitted} \\ \text{by a specific sector} \end{bmatrix} \tag{3.12}$$

$$t_j = t_r \cdot CO_2 \tag{3.13}$$

A vector was then be created of all of the tax revenues of all the different sectors analyzed in the economy.

$$\mathbf{t} = \begin{bmatrix} t_1 \\ \vdots \\ t_j \end{bmatrix} \tag{3.14}$$

### 3.3.2. TAX ON FINAL VALUE ADDED

Carbon tax was then integrated into the cost-push equation. The taxes due to emissions were added to the final value added per sector. This is a tax that each sector must pay purely for emissions associated with the total output of a sector. The way this was done in the model is to add the tax revenue to the value-added of each sector, calculate the new value coefficient including the tax $v_{c_{tax}}$ and then follow the cost-push method again to see the price effects.

$$v_{c_{tax}} = \frac{v_j + t_j}{x_j} \tag{3.15}$$

$$\mathbf{P} = \mathbf{L}' \cdot \mathbf{v_{c_{tax}}} \tag{3.16}$$

### 3.3.3. TAX ON INTERMEDIATE SALES

Taxing intermediate sales is another way of implementing a carbon tax. This method adds the tax on a product before it is sold and used by another sector. To do this, the sectoral tax rate $\tau$ was calculated. This is the total tax revenue for one sector divided by the total output from that one sector. This is shown in Equation 3.17.

$$\tau_{\mathbf{j}} = \frac{t_j}{x_j} \tag{3.17}$$

A diagonal matrix was then constructed with the diagonal elements being 1 plus the sectoral tax rate. The size of this matrix is equal to the matrix of the technical coefficients and the rows and columns align. This diagonal matrix is described in

$$\mathbf{T} = \begin{bmatrix} 1+\tau_1 & 0 & \dots & 0 \\ 0 & 1+\tau_2 & & \vdots \\ \vdots & & \ddots & \\ 0 & \dots & 0 & 1+\tau_n \end{bmatrix} \tag{3.18}$$

Putting a tax on the intermediate sales can be seen as altering the matrix of technical coefficients and so the new cost-push equation can be seen in Equation 3.19.

$$\mathbf{P} = (I - \mathbf{A}' \cdot \mathbf{T})^{-1} \cdot \mathbf{v_c} \tag{3.19}$$

### 3.3.4. COMPETITIVENESS

A competitiveness metric was defined to analyse the impact of carbon tax and CBAM. A positive relative competitiveness means that an EU industry is more competitive than the same industry outside of the EU. The value associated with this is the difference in change in production price. For example, if industry A within the EU increased in production price was 5% and the same industry outside of the EU had a production price increase of 10% then the competitive advantage would be 5% as production prices have increased less in the EU than outside of the EU. This is described in Equation 3.20. This sets the convention for a positive number to represent a competitive advantage for the EU and a negative number to represent a competitive disadvantage for the EU.

$$\text{Relative Competitiveness} = \begin{bmatrix} \text{Rise in production cost in} \\ \text{Sector A outside of the EU} \end{bmatrix} - \begin{bmatrix} \text{Rise in production cost in} \\ \text{Sector A inside of the EU} \end{bmatrix} \tag{3.20}$$

### 3.3.5. DIFFERENT SCENARIOS

In this thesis, two scenarios were compared: first, carbon tax without CBAM to understand the reaction of the economy and competitiveness, and then the combination of carbon tax within the EU and CBAM. This comparison was made to show the impact of carbon tax and CBAM relative to the situation of just carbon tax. The carbon tax is applied to all EU sectors and countries. The sectors to which CBAM was applied in this analysis can be seen in Table 3.4. This represents the first iteration of CBAM sectors being implemented by the EU (European Union, 2023).

In order to apply taxation to only EU countries, non-EU countries, or countries subject to CBAM, filters were developed to easily switch the application of taxes to specific countries and sectors. This approach allows for a carbon tax to be applied to all EU countries and sectors and facilitates the implementation of a carbon tax on CBAM sectors in countries outside the EU. For illustration, two sectors in two EU countries and two sectors in two non-EU countries will be used. To start with, it is necessary to calculate the impacts of a carbon tax within the EU without CBAM. This is done by multiplying the emissions by an EU activation switch, which allows for all non-EU values to be equal to zero, and this is then multiplied by the marginal tax rate. The result is that a tax vector is created where only the EU countries and sectors are taxed. This process can be seen in Figure 3.2.

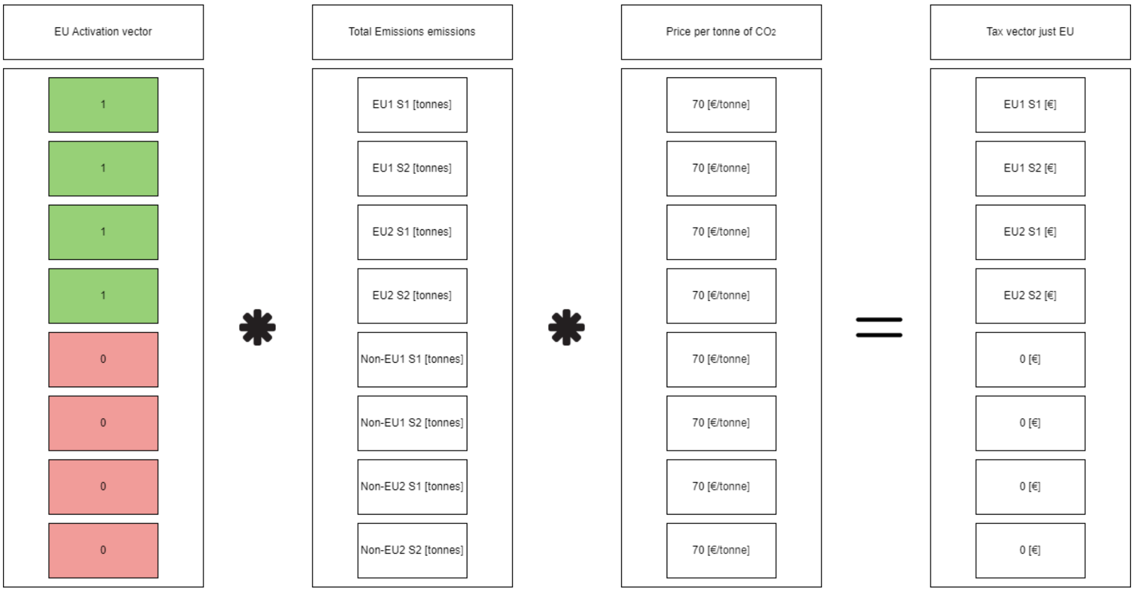


Figure 3.2: An example of the EU switch

A similar process was applied when the analysis needed to be done by adding a CBAM. For illustration purposes, it will be said that sector one is subject to CBAM. So sector one in all non-EU countries is subject to CBAM and so a CBAM activation vector is set up to set all other sectors in other countries to zero as can be seen in Figure 3.3. This gives us a final tax vector that only has taxes for CBAM sectors.

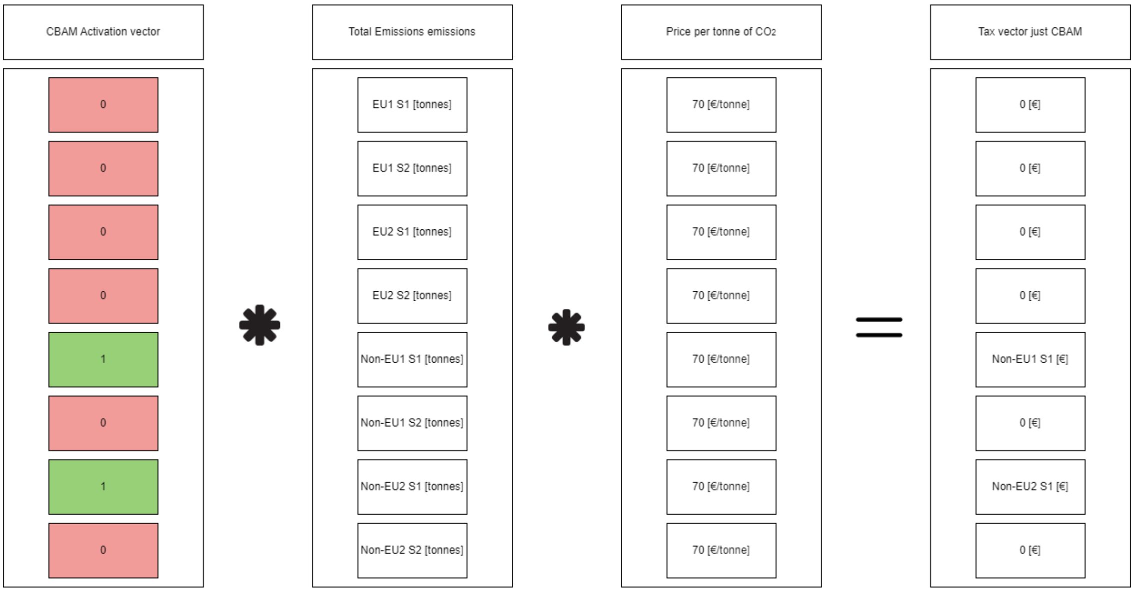


Figure 3.3: An example of the CBAM switch

Finally, a linear combination was made between the EU tax vector and the CBAM tax vector, and this gave us a tax vector which applied a tax for carbon tax within the EU as well as CBAM. This can be seen in Figure 3.4 and this can be used for analysis.

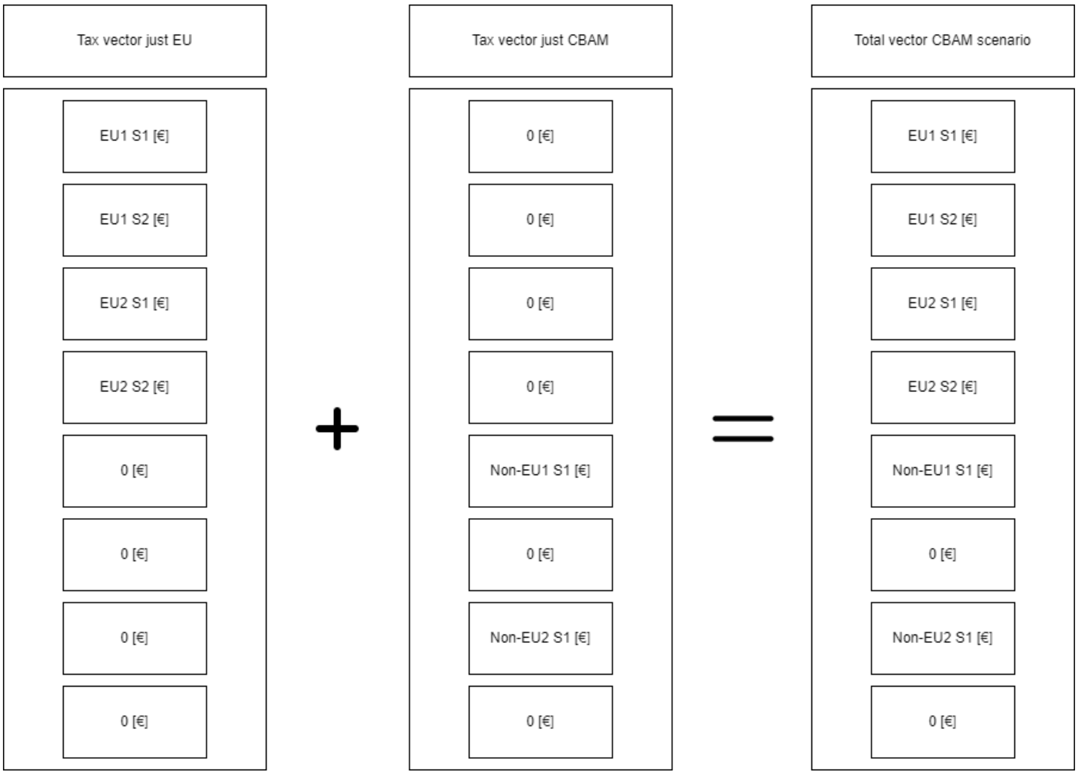


Figure 3.4: Combined carbon tax and CBAM vector

In the model, this example method was applied to large datasets of countries and sectors but the logic and method remain the same. The actual sectors subject to CBAM can be found in the first column of Table 3.4. These are the sectors that are being targeted in the current transition period to CBAM. The sectors to which CBAM is applied in the FIGARO data were selected based on their closest available match. Here, C23 covers the manufacture of non-metallic mineral products, while C24 and C25 cover the manufacture of basic metals and fabricated metal products, excluding machinery. The latter two categories include items like aluminium bolts, nuts, and basic metal pieces. Additionally, C20 covers the manufacture of chemicals and chemical products, and D35 pertains to the electricity sector. However, due to the limited granularity of the FIGARO data, certain generalizations were necessary. For instance, to apply CBAM to fertilizers, it was applied to the broader category of "Manufacture of chemicals and chemical products." As a result, more products are included beyond just fertilizers, which means the results are likely to be an overestimate compared to the real impact on fertilizers alone. Please refer to section A.1 to see a full breakdown of the sub-sectors. A limitation of this method is that it does not provide accurate results for non-EU countries themselves, as not all their trade flows are directed to the EU. This is discussed further in section 4.3.

Table 3.4: The sectors to which CBAM was applied and the corresponding FIGARO sectors

| **CBAM Sectors** | **FIGARO Sector** | **FIGARO Sector code** | **Sub-sector code** |
|---|---|---|---|
| Cement | Manufacturing | C | C23 |
| Iron and steel | Manufacturing | C | C24 & C25 |
| Aluminium | Manufacturing | C | C25 |
| Fertilisers | Manufacturing | C | C20 |
| Electricity & Hydrogen | Electricity, gas, steam & air co. | D | D35 |

## 3.4. PROCESSING OF RESULTS

This methodology gave a series of price factors, which described the factor increase in production price, for every sub-sector in every country present in the FIGARO database. These price factors are then converted into percentages for ease of analysis and further grouped by country and industry. Within the EU, a country, sector or industry; the weighted average with respect to the value-added was taken. This means that the percentage increase for a sector which forms a large contribution to the economy has a bigger impact on the average than the percentage change for a sector which has a smaller contribution to the economy. For all simulations, a carbon tax of €70/tonne was used as this is the value that EU-ETS has stabilized at as of May 2024 (Trading-Economics, 2024).

## 3.5. CONCLUSION

Starting from the data set, the different aspects of IO data were broken down into three main categories. This flows between sectors, the value added and the final demand for the output for all of the sectors. Subsequently, the assumptions of the model were discussed and the core elements of cost-push input-output analysis were outlined. Based on this, two methods for implementing carbon tax were presented. One of these methods is adding a carbon tax onto the final value added of a sector, which taxes them based on their activities. The second is placing a tax on intermediate sales, so the cost of intermediate products becomes higher due to the emissions associated with them. This has more cascading effects on the economy. Both of these methods were used and the results from each can be seen in chapter 4. Lastly, the convention for competitiveness was defined and a brief explanation for how different scenarios can be modelled using filters was mentioned.

# 4 | Results & Discussion

Using the methods described in chapter 3, the impact of carbon pricing and CBAM per sector and per industry on production costs as well as competitiveness was analyzed. The two methods described were modelled in parallel, namely tax on final value-added and tax on intermediate sales. Firstly, the results for tax on value-added will be shown, and this will be taken as the baseline method. This is due to tax on value-added being the prominent method in existing research on the topic of carbon pricing using input-output modeling, and there being limited research using tax on intermediate sales. This method will be fully analysed and discussed in order to contribute to scientific literature on the topic using this method. The results are extended with comparing the results of the tax on intermediate sales method. This is relatively new and there is little literature on this therefore the second part of these results contributes to this field by expanding the methodology, and results and providing an initial analysis of the compared results.

The results begin with the baseline results. These are presented and discussed in section 4.1, focusing on increases in production prices and competitiveness, and impacts on the EU as a whole and on individual EU countries. Then, the impact on production prices of industries is examined, with a deep dive into the manufacturing sectors, as these presented some interesting results. Competitiveness is not calculated on the individual country level, as countries do not produce the exact same output, and therefore the current definition of competitiveness is not applicable. The last part of this section discusses the baseline results and analyzes the limitations of the CBAM model. Then, in section 4.2, the results of the intermediate sales method are compared to the baseline results, and these are discussed, providing potential reasons for the discrepancies. This section culminates in analyzing the mechanics of the model using intermediate sales and concludes possible dependencies and areas for further research. Lastly, this chapter estimates the potential impacts on EU exports and reflects on the political economy of this policy and what the results mean for it. Additionally, the effectiveness of carbon pricing in the energy transition is reflected upon.

## 4.1. BASELINE - RESULTS & DISCUSSION OF TAX ON VALUE ADDED

The results for tax on value-added will be presented and discussed in parallel in this section. The origin of this research started with looking at the impacts of production prices on the EU as this may lead to carbon leakage and negative effects on competitiveness for the EU. The results start very broad looking at the EU as a whole and then steadily dive deeper to look at the effect on individual countries, industries and some sub-sectors. The effects of just a carbon tax within the EU are presented along with carbon tax and CBAM combined. The difference between these results can also give interesting insights into the reliance of imports of specific countries and industries and this will be touched upon.

### 4.1.1. EU IMPACT UNDER A €70 CARBON TAX WITH & WITHOUT CBAM

Starting broadly, the impacts of carbon tax with and without CBAM can be seen in the first row of Table 4.1. This shows that when only an EU carbon tax is implemented, the weighted average production price increases by 1.02%, which is to be expected as extra taxes due to emissions are priced in, making goods more expensive. When CBAM is implemented, an additional increase to 1.26% can be seen, which demonstrates that production prices within the EU get even more expensive due to the increased costs of imports used as inputs in production. Looking at the change in competitiveness experienced, which can be seen in the second row Table 4.1, a competitive disadvantage of -0.98% is observed when only the domestic carbon tax is implemented, which turns into a competitive advantage when CBAM is implemented. This demonstrates that CBAM, in this case, is successful in protecting the EU's competitiveness. An important note is that this represents the competitiveness of industries that sell to EU countries. This positive competitiveness means that it is cheaper for entities within the EU to purchase goods and services from within the EU rather than outside of the EU. For entities outside of the EU, the price of EU goods will still remain relatively higher after the implementation of carbon tax and CBAM, and so it is necessary to look at the impacts on export volumes, which will be discussed further in section 4.7.

Table 4.1: Comparison of Changes in EU Production Cost and Competitiveness with and without CBAM

| **EU weighted average** | **Without CBAM** | **With CBAM** |
|---|---|---|
| Change in production cost | 1.02% | 1.26% |
| Change in relative competitiveness | -0.98% | 1.46% |

Schotten et al. (2021) describes a moderate price increase as being in the range of 0-2% increase in price. Using this it can be said the price increase experienced by the EU at 1.26% is fairly moderate. This is, of course, a weighted average for the EU, and so there will be countries and industries within the EU that are hit harder than the average. It is interesting to break down the EU aggregate into two subcategories, namely looking at the difference in how specific countries are impacted and also how different industries are impacted. First of all, the impact on countries will be discussed in subsection 4.1.2.

### 4.1.2. EU COUNTRY IMPACT UNDER A €70 CARBON TAX WITH & WITHOUT CBAM

The most impacted countries in the EU under carbon tax and CBAM are Poland, Bulgaria, and Estonia. This is seen in Figure 4.1, with production price increases ranging from 2.09% to 3.40% with just carbon tax and going up to 2.74% to 3.84% with CBAM included. One would expect that countries such as Luxembourg, Malta, & Cyprus would be hit the hardest due to carbon taxation as the share of fossil fuels in their energy mix is relatively high (Eurostat, 2023a). It is therefore somewhat surprising to see this result. This can be explained by looking at the contribution certain industries have towards the total Gross Domestic Product (GDP) of a country. GDP takes into account all of the goods and services of a country, and so even though the dependency on fossil fuels may be relatively high if the total weight of the energy sector in the economy is relatively low, then the weighted impact of those fossil fuels on the whole country's economy is relatively low. As a reminder: all values calculated are weighted with respect to value-added, meaning the portion they contribute to the Gross Domestic Product

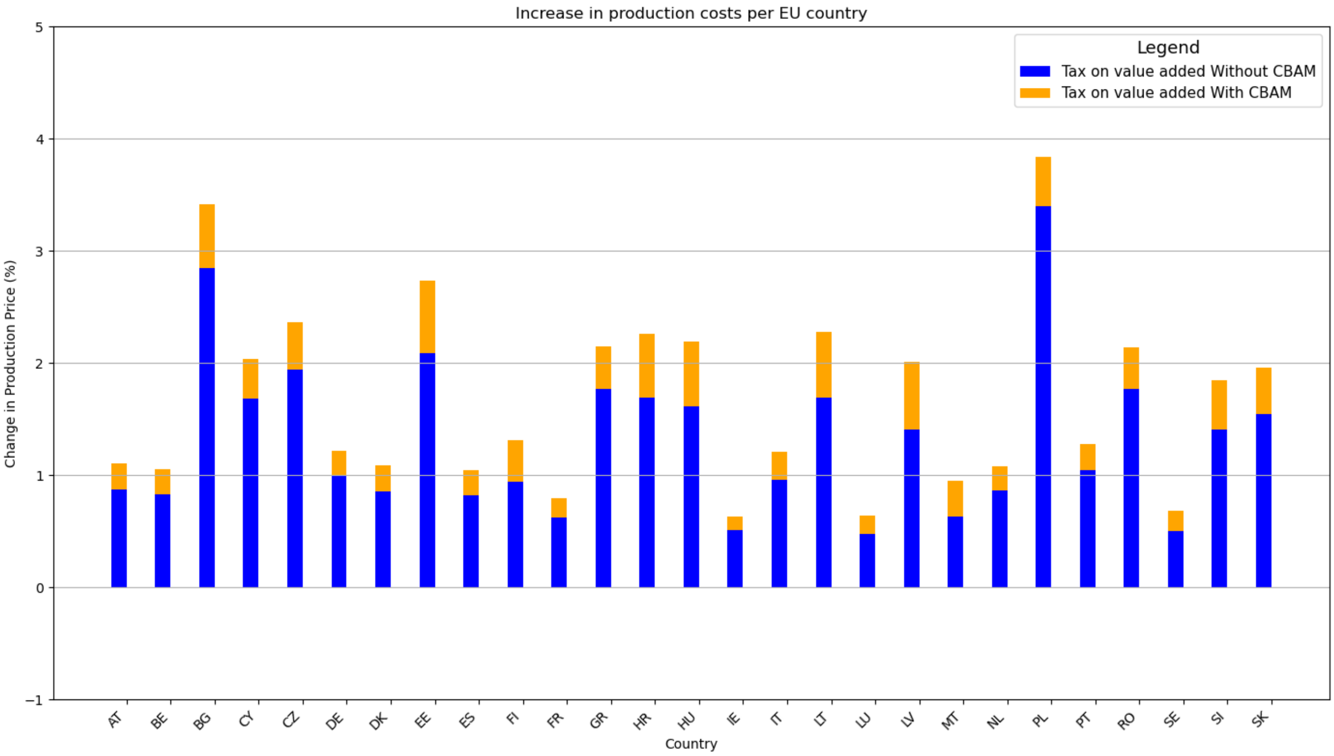


Figure 4.1: Change in Production Price per EU country with CBAM through tax on value added

These results are explained by the fact that energy-intensive sectors like mining, quarrying, and agriculture form a large part of the economies of places such as Poland, Bulgaria, Estonia, and other Eastern European countries, as can be seen in Figure 4.2 & Figure 4.3. These sectors require a lot of heavy machinery, and agriculture usually uses carbon-intensive fertilizers; this causes sharp increases in production costs as the production of these fertilizers is now much more expensive and this carries onto the cost of agriculture. This explains why certain countries experience higher increases in production prices than others due to the implementation of carbon tax.

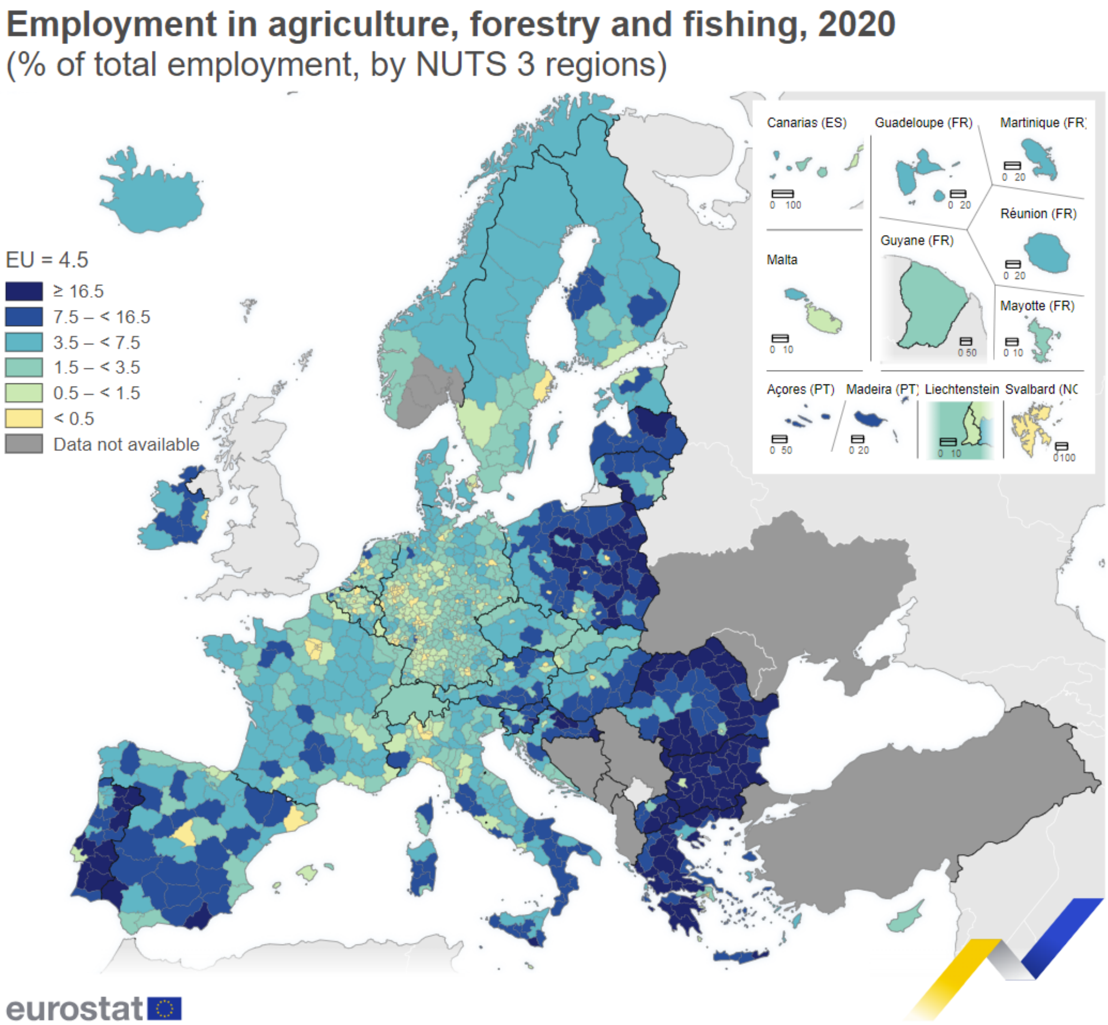


Figure 4.2: Importance of agriculture throughout Europe (Eurostat, 2023b)

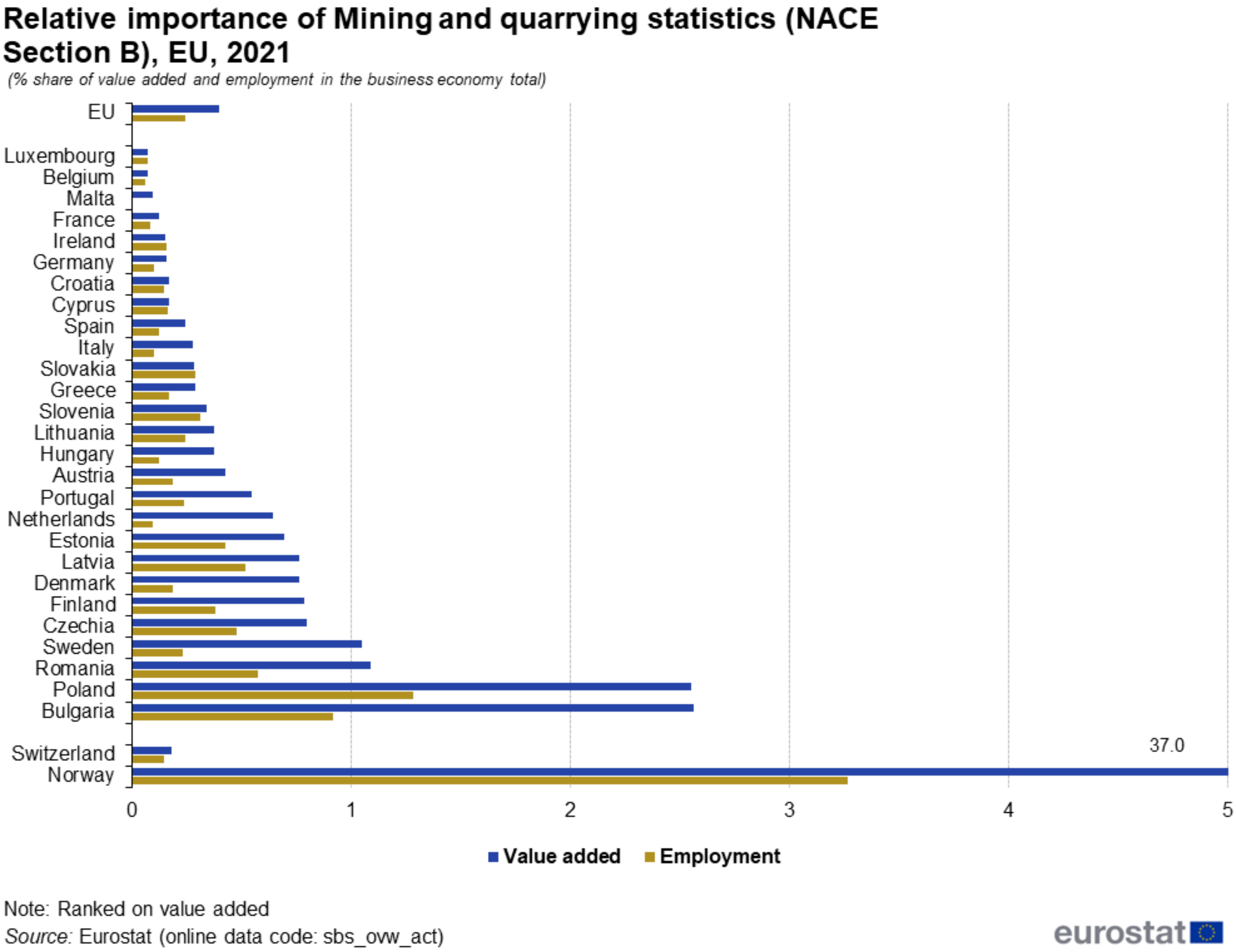


Figure 4.3: Importance of mining & quarrying throughout Europe (Eurostat, 2024a)

Looking into the increase in production price due to CBAM itself, as can be seen in Figure 4.4, provides further insights into the reliance on imports of countries. Countries such as Estonia, Latvia, Lithuania, Hungary, and Croatia are amongst the hardest hit, experiencing over a 0.5% increase in production price CBAM - a measure designed to protect the EU. This could be attributed to a large portion of imports in these countries being things like heavy machinery, which have a high aluminium, iron, & steel content, which is carbon-intensive and a CBAM sector (Investment and Development Agency of Latvia, 2024).

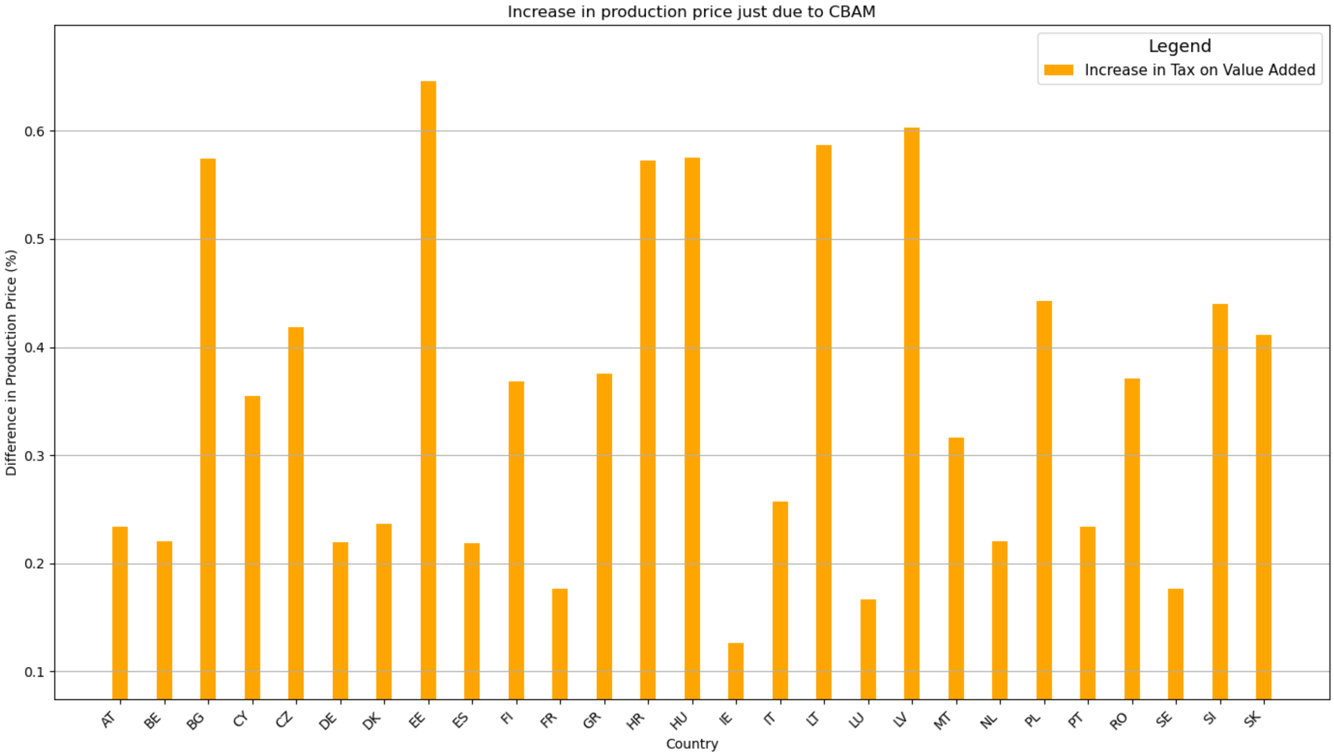


Figure 4.4: Difference in production cost purely due to the implementation of the CBAM component

Looking at the distributed impacts throughout Europe, it can be seen that the impacts of carbon pricing disproportionately hit Eastern European countries due to larger parts of their economy relying on carbon-intensive sectors like agriculture and mining & quarrying. The implementation of CBAM also follows similar trends due to high proportions of imports in these countries being products with a lot of emissions associated with them in production. Now that the geographic impact has been discussed throughout Europe, an industry analysis can be done.

### 4.1.3. EU industry impact under a €70 carbon tax with & without CBAM

Now that the impact on different countries has been analyzed, the industry impact is looked at. As done previously, production price increases will be examined as well as discussed and insights from the results on competitiveness will be highlighted.

#### Production prices

In Figure 4.5 it is observed that the top three most impacted sectors range from increases in production price of 2.23% to 9.55% without CBAM and increase to 2.54% to 10.10% with it. The top three most impacted industries — Energy, Mining & Quarrying, and Agriculture — are in line with expectations due to their high emission intensity. Energy has high carbon emissions associated with non-renewable fossil fuel energy sources, Mining & Quarrying are also expected due to the energy-intensive process of using heavy machinery to extract raw materials, as well as smelting and processing these into final products. Agriculture uses lots of fertilizer as well as machinery in its process which are both emission-intensive. Transportation is also an impacted sector, which is in line with expectations due to the emissions associated with petroleum fuels needed to power modes of transportation.

One of the other industries that rises above the 2% threshold, discussed in (Schotten et al., 2021), is manufacturing. This requires further analysis, as manufacturing has a variety of sub-sectors and is also one of the sectors most impacted by the implementation of CBAM itself, as seen in Figure 4.6. It experiences a production price increase of over 0.5%, showing that it has a heavy reliance on imports from CBAM sectors. This requires a deeper analysis, which will be done in subsection 4.1.4.

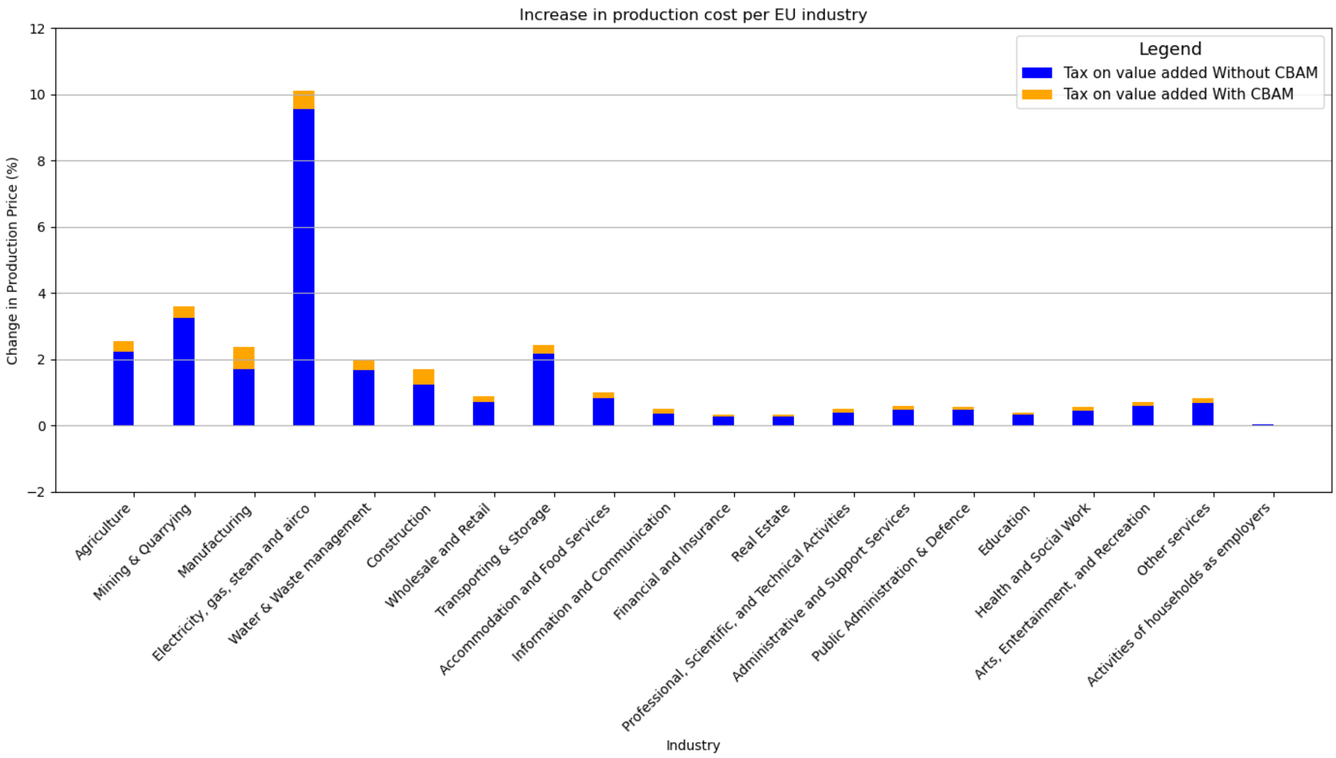


Figure 4.5: Change in Production Price per EU industries with CBAM through tax on value added

Looking specifically at the increases in production prices due to just CBAM in Figure 4.6, another sector that is heavily impacted by the implementation of CBAM is the construction sector. This is due to the import of materials like steel from outside of the EU, which is emissions-intensive. These will now cost more due to the implementation of CBAM. The energy sector is also hit relatively hard, and this is likely due to the high volumes of imported gas, which is now taxed (eurostat, 2024). The effects on competitiveness are described in the next subsection.

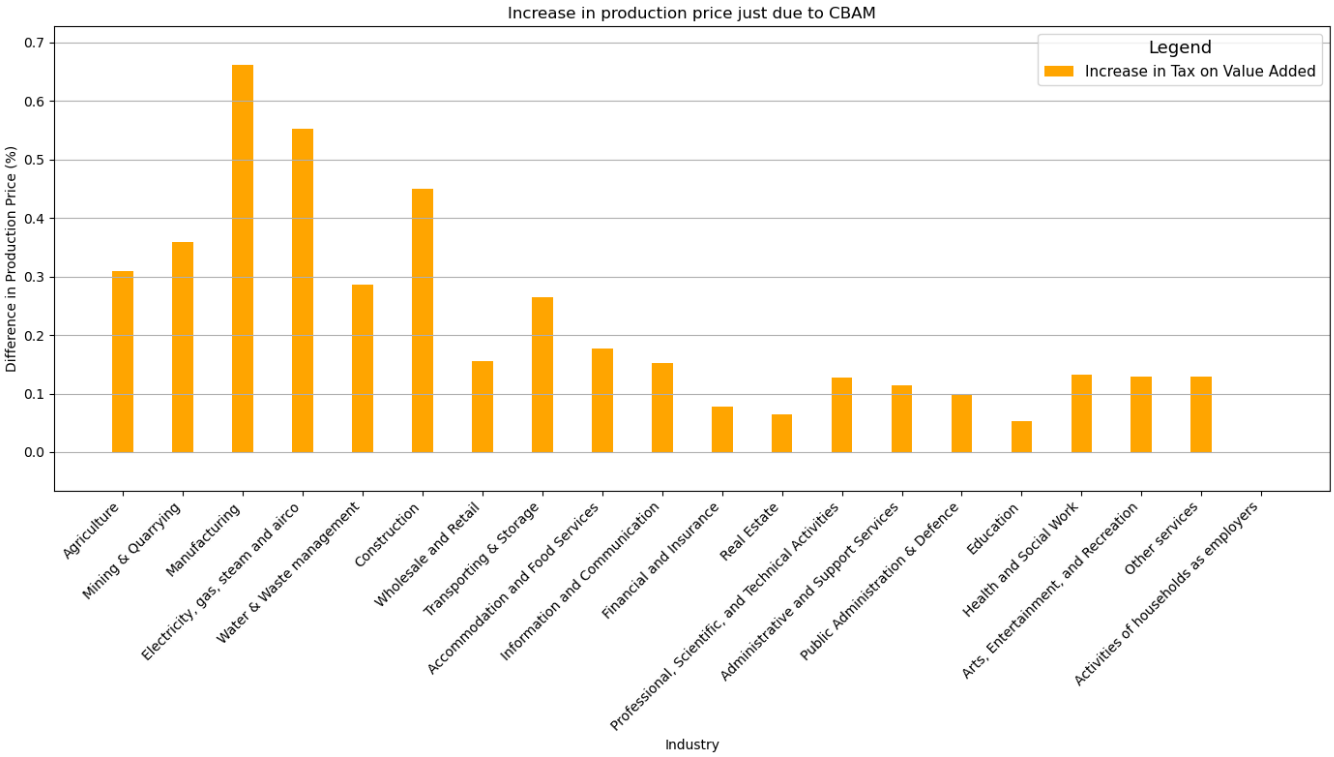


Figure 4.6: Difference in production cost purely due to the implementation of the CBAM component

### COMPETITIVENESS

The industries that face the biggest increases in production costs under a domestic carbon tax are also the ones that suffer the biggest competitive disadvantage without CBAM. Something interesting happens, however, when CBAM is implemented. The energy sector sees a large competitive advantage of 26.29%, much greater than the original competitive disadvantage of -9.50% under the domestic carbon tax. Due to cross-border trade in electricity being fairly limited currently, this competitive advantage does not likely translate into significant trade advantages. Large competitiveness increases may cause issues with the WTO because it may stimulate trade wars and harm global trade (Kuusi et al., 2020). This will be discussed further later in section 4.8.

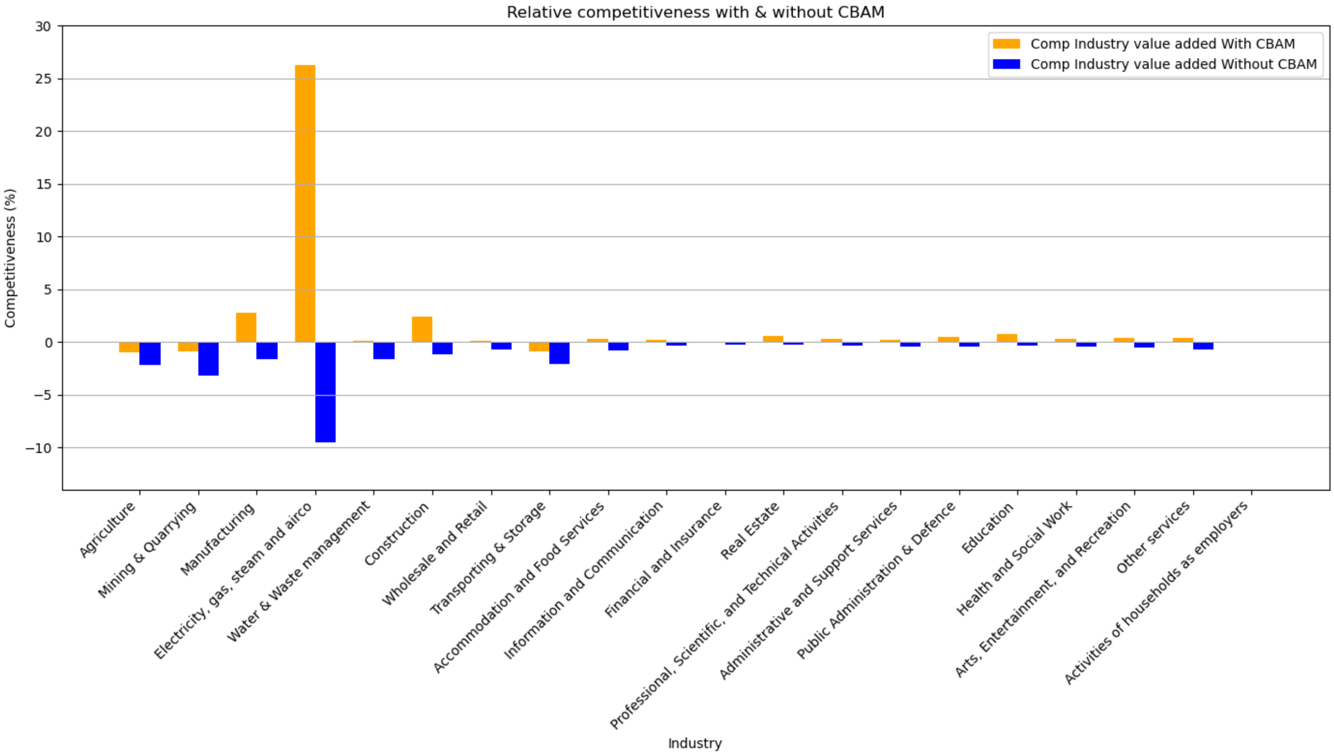


Figure 4.7: Relative competitiveness per EU industry with CBAM through tax on value added

A systematic error appears when looking at the granularity of the FIGARO data and should be reflected upon. The CBAM only applies specifically to Electricity & Hydrogen, but due to the granularity of the model, the tax had to be applied to the whole Electricity, Gas, Steam & Air Conditioning industry, which is broader. Therefore, the import tax is likely being applied to extra sectors. Because this is a systematic error, the comparison should still be effective, and the results valid. The large change in competitiveness is likely due to the much dirtier energy systems found outside of the EU. These have higher emissions, which in turn lead to more import taxes needing to be paid. Another factor contributing to this large variation in the energy sector is the EU's dependency on imported gas. When CBAM is implemented EU gas becomes more competitive compared to the large amount of gas it imports. (eurostat, 2024).

Several sectors does not gain a competitive advantage when CBAM is implemented, and those are the transportation, mining & quarrying and the agricultural sectors. These are at a small but negative competitive disadvantage of approximately -1%. This would indicate a shortcoming of the CBAM policy. However, these are also a very domestic industries; they are not activities that can easily be sold across borders and therefore will not likely result in any leakage due to a lack of competitiveness.

### 4.1.4. MANUFACTURING BREAKDOWN

One of the industries that suffered the most from the implementation of CBAM and had a total production price increase of over 2% was the manufacturing industry. This is also an industry that can and has easily been shifted overseas over the last two decades (Dachs et al., 2012). As an industry of importance, a further breakdown is done to interpret the results.

Initially, it is seen in Figure 4.8 that a couple of sub-sectors are hit disproportionately. For example, non-metallic mineral products and basic materials. Unfortunately, the FIGARO database does not break this down any further, so it is difficult to say which specific products are most impacted. A conclusion is that many basic materials will increase in price significantly, a fact that holds regardless of competitiveness. This may cause direct impacts on consumers. A reassuring note is that the manufacture of pharmaceuticals, remains relatively low in production cost increases, meaning that people who need access to prescriptions will only experience small to moderate price increases, which revenue recycling schemes could mitigate. Revenue recycling schemes could come in the form of tax benefits, and capital tax cuts for disproportionally affected parts of the population or sectors; this has been modelled to make carbon tax progressive (Beck et al., 2015). Increases in production prices due to the implementation of CBAM show that all manufacturing sectors rely on imports, especially coke & petroleum products and basic materials.

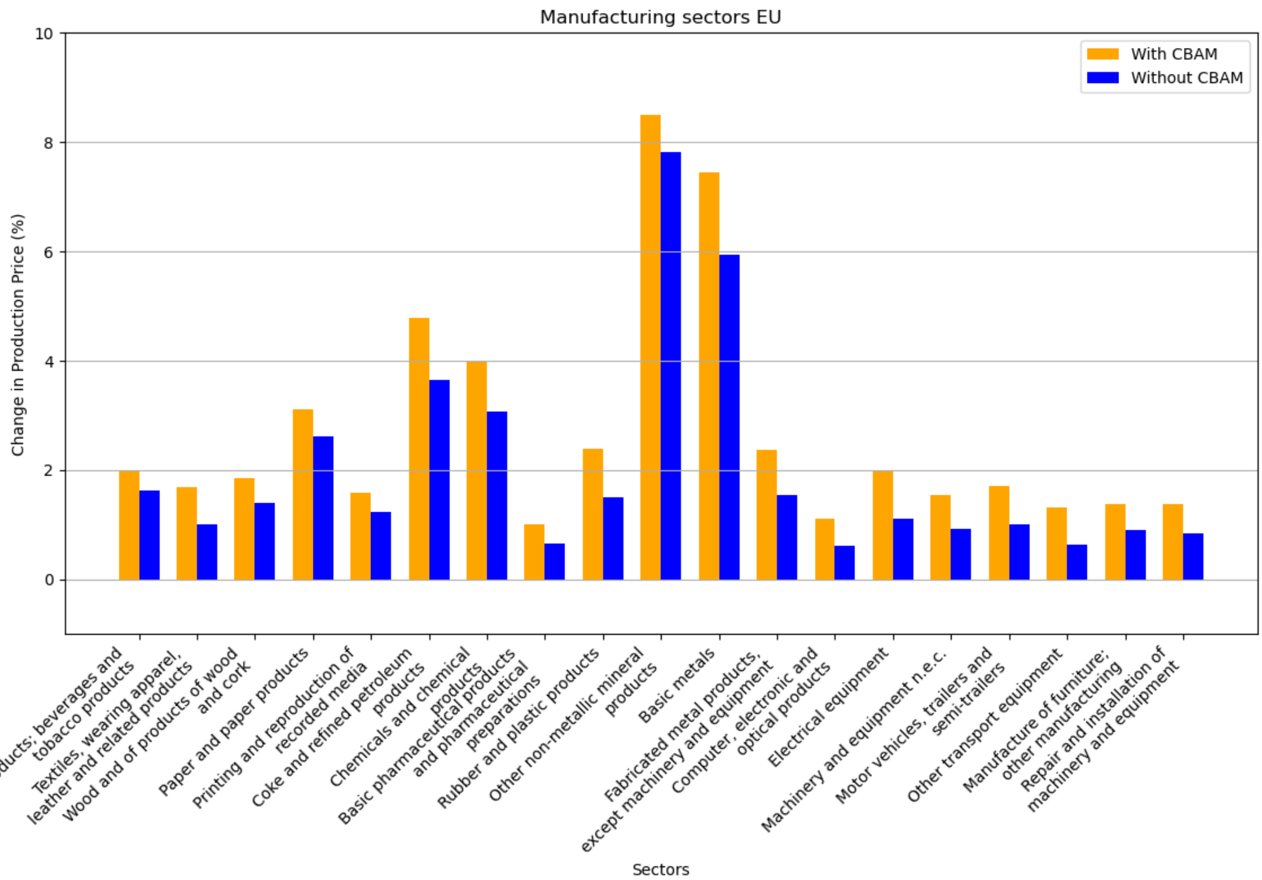


Figure 4.8: Change in production prices of the manufacturing industry

Looking at the competitiveness in Figure 4.9 reveals large competitive advantages in non-metallic mineral products, but a continued competitive disadvantage for the manufacture of coke and refined petroleum products. This sector remains at a competitive disadvantage of over -2%, meaning that it would still be cheaper to manufacture outside of the EU. This could be cause for concern, as producers might move their manufacturing outside of the EU, leading to carbon leakage.

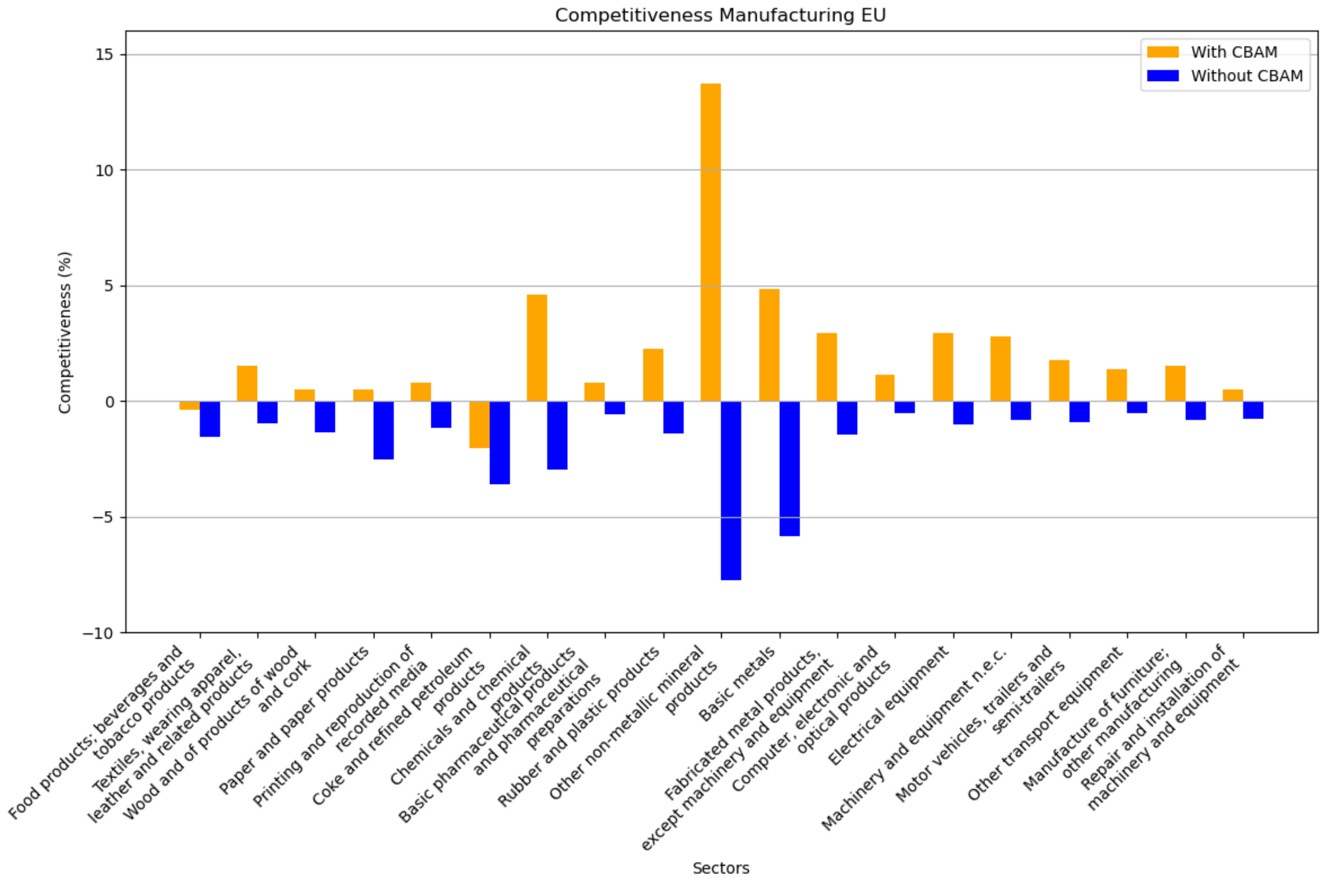


Figure 4.9: Change in competitiveness in the manufacturing industry

## 4.2. A COMPARISON OF BASELINE AND TAX ON INTERMEDIATE SALES

The second method outlined in chapter 3 was applying the tax to intermediate sales. This method is referred to in the literature, although it was not chosen in previous research on the topic (Schotten et al., 2021). It has been decided to execute this method directly as is done in the theory to compare it to the baseline results and analyze the differences that may arise. One assumption was made, which is the sectoral tax rate for this intermediate sales method as this is not defined in literature. This was assumed to be the total tax revenue for a sector divided by the total intermediate output, as described in subsection 3.3.3 - this was derived from unit analysis. In this case, CBAM is implemented in the same sectors as previously.

### 4.2.1. IMPACT ON THE EU AS A WHOLE

Looking at the macro EU level, mixed results can be observed in the increase in production costs when using the tax on intermediate sales method. This can be seen in Figure 4.10. The intermediate sales method yields a slightly lower increase in production price than the tax on value-added method in the scenario without CBAM. When adding in CBAM, the total increase in production price due to carbon tax and CBAM is 1.26% for the tax on value-added and 1.47% for the tax on intermediate sales. The latter method now shows a higher increase in production price. What was described as a moderate increase in the initial discussion of results in chapter 4—between 0-2% (Schotten et al., 2021)—is still observed as the total increases remain below the 2% threshold. A similar trend can be noticed in Figure 4.11 concerning competitiveness, where intermediate sales initially show a smaller loss in competitiveness than value-added but a greater gain in competitiveness after CBAM.

The differences in the methods are driven by the mechanics of the model. Each model gives a higher or lower result than the other based on variables such as taxation rates of input sectors as well as whether the sector has a high value-added-to-output ratio or not. These are expanded on in subsection 4.2.4. A theme found in literature on sales tax is that there is a risk of double taxation — also known as cascading tax, which accounts for the higher and economically less desirable impacts (Shome, 1995). This occurs because the tax is applied to the gross value of the transaction rather than purely the value added, so taxes can accumulate along the supply chain to the final consumer. The result is that for sectors with more complicated supply chains, the impact tends to be greater; meaning in the context of carbon pricing, the total tax paid on a product due to the emissions is greater than the embodied emissions would warrant. It is unclear whether this happens in the model. Due to the model being based on a system of linear equations that are solved simultaneously, a logical hypothesis is that it does not occur. To test this hypothesis, further research is needed into the mechanics of the models. A recommendation for future research would be to try to quantify the impact of this cascading tax in input-output modelling, as this currently falls outside the scope. Before that, it is valuable to briefly look further into the output of the model before analyzing what the possible causes of the differences could be in subsection 4.2.4.

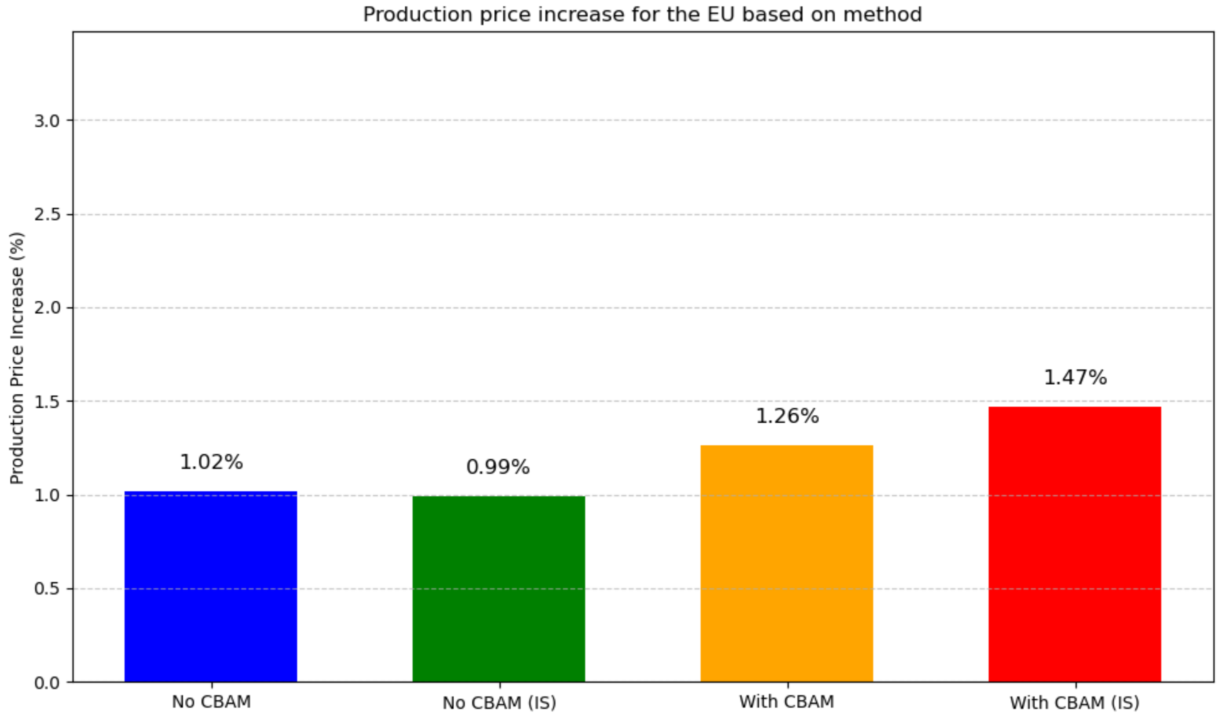


Figure 4.10: Comparative impact of baseline against and tax on intermediate sales on EU production prices

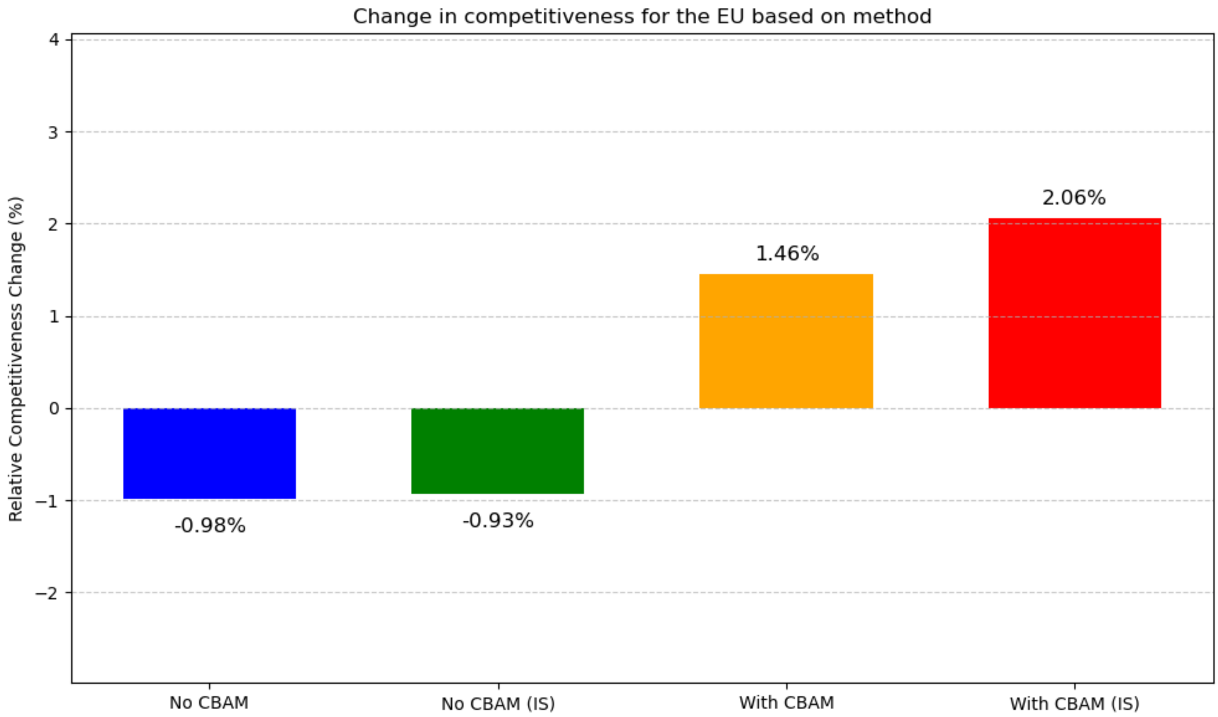


Figure 4.11: Comparative impact of baseline against and tax on intermediate sales on EU competitiveness

### 4.2.2. IMPACT ON EU COUNTRIES & INDUSTRIES

IMPACT ON EU COUNTRIES

The graphs below are stacked bar charts to display the impact. The blue and red bars represent the increase in production costs due to the carbon tax alone, while the yellow and green bars show the relative increase due to the implementation of CBAM. The total height of each bar is the total increase in production costs from both the carbon tax and CBAM. Starting with the blue and red bars in Figure 4.12, which represent a tax on value-added and tax on intermediate sales respectively, both without CBAM, it can be seen that, except for Bulgaria and Poland, the results of the two methods seem to be generally in line with each other. When CBAM is implemented, the tax on intermediate sales method generally appears to be higher.

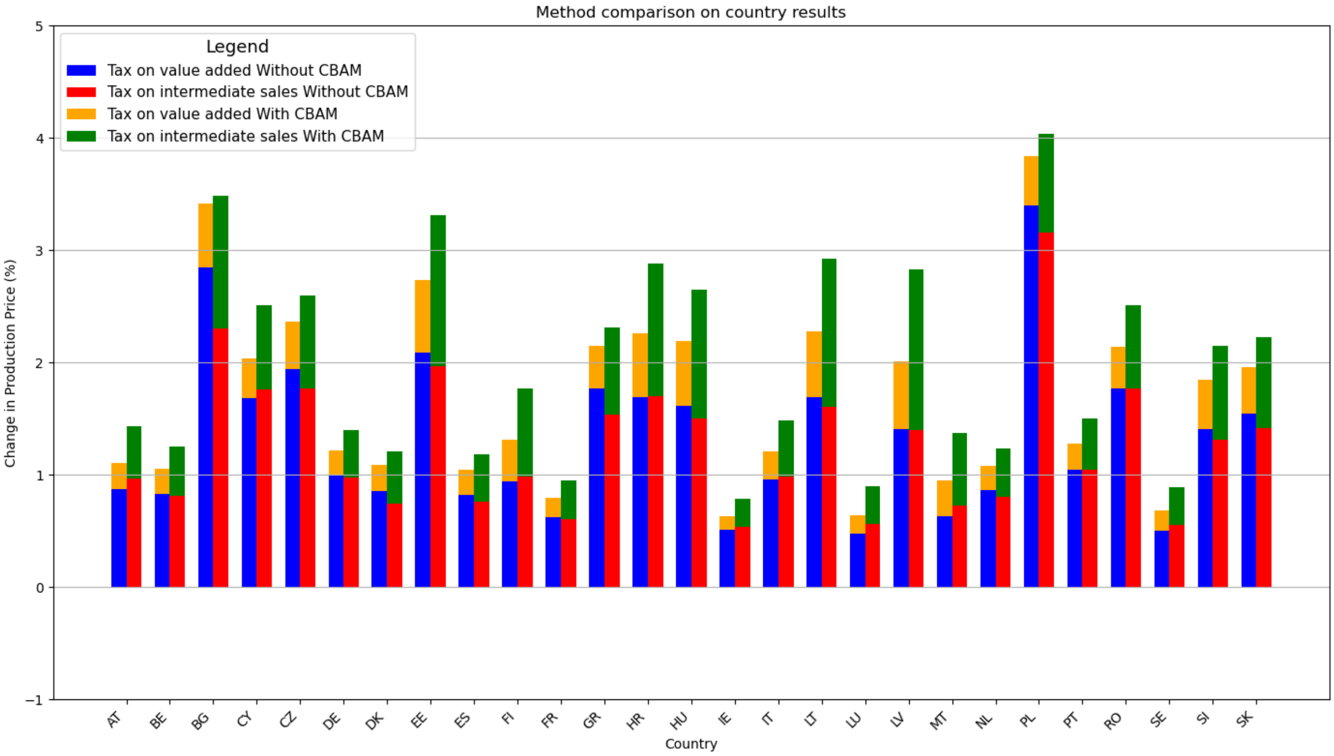


Figure 4.12: Comparative impact of baseline against and tax on intermediate sales on countries

### IMPACT ON EU INDUSTRIES

When looking at specific industries, there is less of a clear trend. For some industries, the tax on value-added yields higher price increases, while for others, intermediate sales yield higher increases. Looking at the most impacted sectors, the top two most impacted sectors are consistent with the tax on value-added method, but the third differs. In the tax on value-added method, the third most impacted sector is Agriculture, whereas in the tax on intermediate sales method, it is Manufacturing.

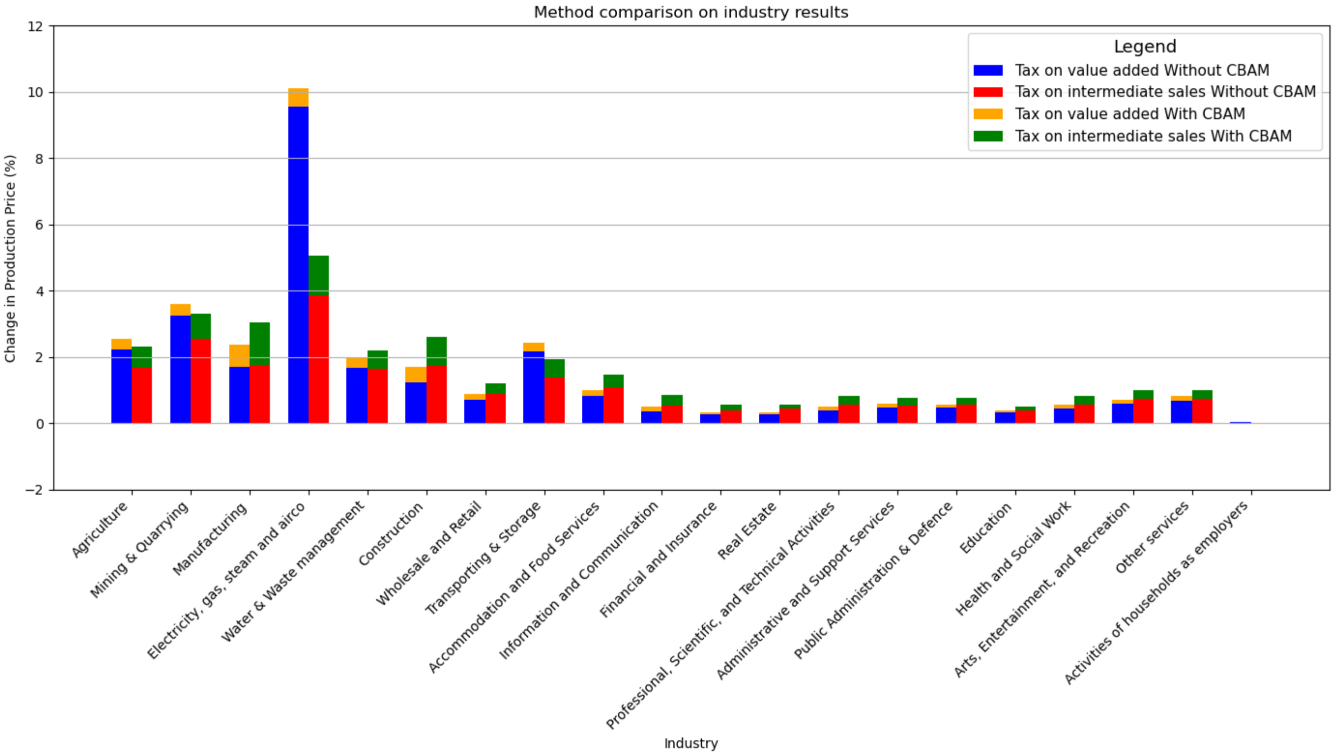


Figure 4.13: Comparative impact of baseline against and tax on intermediate sales on industries

### 4.2.3. IMPACT OF IMPLEMENTING CBAM

To gain insight into the increase in production price purely due to the addition of CBAM, Figure 4.14 and Figure 4.15 can be examined. The countries most affected in the baseline case, due to their reliance on imports, are also the most impacted under the tax on intermediate sales. For industries, it can be seen that those with very complex supply chains are impacted as well as industries that rely heavily on imports, such as agriculture, are also significantly affected, as the EU is a net importer of fertilizers (Fertilizers-Europe, 2023). The main takeaway from the comparisons is that the tax on intermediate sales models has a much higher impact of CBAM than the tax on value-added. This difference is likely due to the non-linear behaviour of the intermediate sales method when number of inputs in a production process becomes higher. This will be further discussed in subsection 4.2.4.

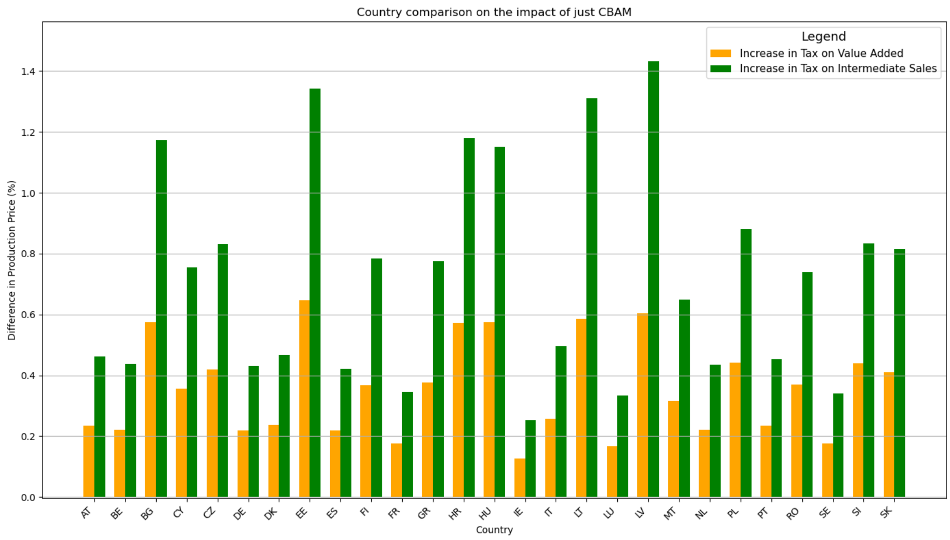


Figure 4.14: Difference in production cost of countries purely due to the implementation of the CBAM component

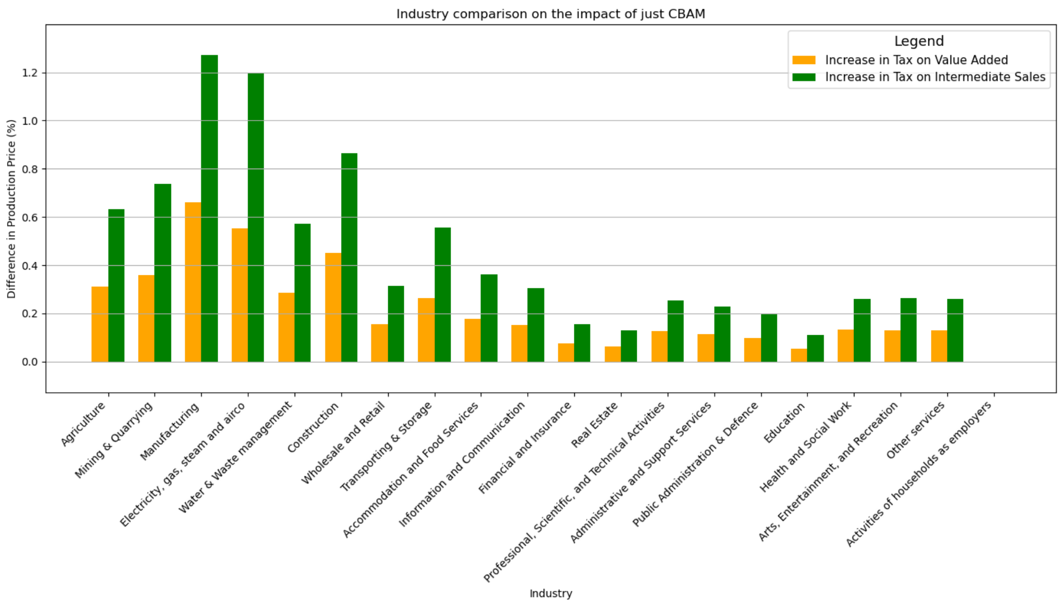


Figure 4.15: Difference in production cost of industries purely due to the implementation of the CBAM component

### 4.2.4. SENSITIVITY ANALYSIS

A sensitivity analysis was done to gain insight into which factors cause differences between the two methods. First of all a simple example was be derived, which formed the basis of the sensitivity analysis. A situation where two sectors were present was initially analyzed, this was then be expanded to an example with three sectors and finally, a sensitivity analysis will be done with four sectors, where different reliances on imports are evaluated.

SIMPLIFIED EXAMPLE

Gaining an understanding of the mechanics of the two methods provided insight into the factors that impact the model and, thereby, the differences in results. The model used the equations as described in chapter 3. How these equations function for a specific sector can be seen in Equation 4.1 for value-added and Equation 4.2 for intermediate sales. It can be observed that the tax is applied to the value-added coefficient in Equation 4.1 and to the gross value of the input sector in Equation 4.2.

$$p_j = a_{1j} p_1 + a_{2j} p_2 + \ldots + a_{nj} p_n + v_{cj} \left(1 + \tau_j\right), \quad j = 1, \ldots, n \tag{4.1}$$

$$p_j = a_{1j} (1 + \tau_1) p_1 + a_{2j} (1 + \tau_2) p_2 + \ldots + a_{nj} (1 + \tau_n) p_n + v_{cj}, \quad j = 1, \ldots, n \tag{4.2}$$

The following parameters were defined for this simplified model.

$$A = \begin{bmatrix} 0.2 & 0.3 \\ 0.4 & 0.1 \end{bmatrix} \tag{4.3}$$

where the sectoral tax rates for the tax on value-added and the tax on intermediate sales are Equation 4.4 and Equation 4.5, respectively.

$$\tau = \frac{t_j}{v_j} \tag{4.4}$$

$$\tau = \frac{t_j}{x_j} \tag{4.5}$$

This yielded Equation 4.6 and Equation 4.7. For the derivation please see appendix section B.4. The same logic can be applied to calculated the new price of sector 2 and these sets of equations are then solved simultaneously.

$$p_{1\,new} = 0.2 + 0.4 + v_{c1} (1 + \tau_1) \tag{4.6}$$

$$p_{1\,new} = 0.3 \cdot (1 + \tau_1) + 0.1 \cdot (1 + \tau_2) + v_{c1} \tag{4.7}$$

TESTING DEPENDENCY ON VARIABLES WITH TWO SECTORS

Now that the simplified equations have been formulated, variables can be altered and plotted to understand how they impact the outcomes. The first scenario to be examined is what happens when the tax rate is fixed and the value added is varied. Secondly, the value added will be fixed and the tax rate will be varied.

The results for the first scenario can be found in Figure 4.16. Here, the tax rates for both Sector 1 and Sector 2 are the same, and only the value added is varied. Specifically, this refers to the value coefficient - the value added to the economy divided by the total output. It can be observed that when a sector produces a large amount of value added relative to the total output—towards the right of the graph—the tax on value-added method generally results in a smaller price increase compared to intermediate sales. Conversely, if a sector produces relatively little value added compared to the total output, the difference in output between the two methods is more moderate.

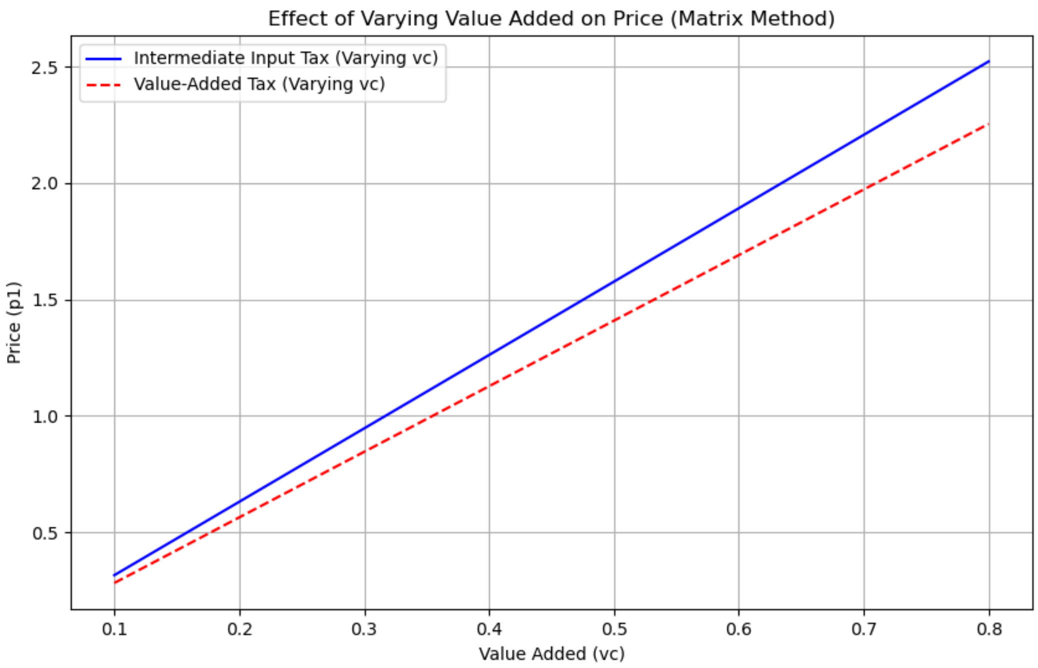


Figure 4.16: The price given by both methods when the value coefficient is varied

Moving to the next scenario, if the value added remains fixed, but the tax rate varies, while still ensuring that the tax rate is equal for both sectors one and two the response in Figure 4.17 is seen. The two methods start at the same output level. However, the intermediate sales method increases much faster in a non-linear fashion compared to the tax on value-added method which remains linear in response. What is important to note is that for the tax under both methods to be equal to each other, the total output must be equal to the total value added, which is an ideal situation and unlikely in reality.


Figure 4.17: The price given by both methods when tau is varied but equal for both sectors

The second scenario, where the tax rate is the same for both sectors, is unlikely to occur in reality. Therefore, another scenario is considered where the value added remains fixed, while the tax rate for Sector 2 varies, and the tax rate for Sector 1 remains fixed at 0.1. The results shown in Figure 4.18 indicate that when the tax rate for Sector 2 is lower than that of Sector 1, the tax on value-added will generally results in a larger price increase. When the tax rate of sector two is higher than sector one then the tax on intermediate sales method produces a high price increase.

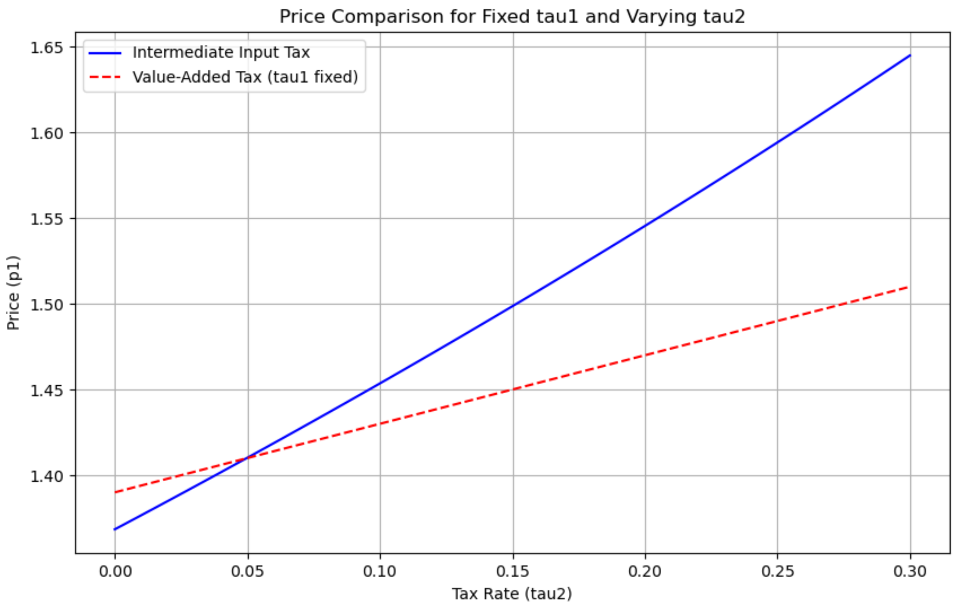


Figure 4.18: The price given by both methods when tau1 is fixed and tau2 varies

### TESTING DEPENDENCY ON VARIABLES WITH THREE SECTORS

In a similar way to the previous example, a simple model was extended to three sectors to see what differences show between the two methods. For this example, a uniform A matrix was chosen, such that all of the components were equal to 0.2, and base values were equal to 1. The updated equations can be seen in Equation 4.8 and Equation 4.9. The same logic can be used to write the equations for the new price of sector 2.

$$p_{1\,new} = 0.2 + 0.2 + 0.2 + v_{cj}\,(1+\tau_1) \tag{4.8}$$

$$p_{1\,new} = 0.2\cdot(1+\tau_1) + 0.2\cdot(1+\tau_2) + 0.2\cdot(1+\tau_3) + v_{c1} \tag{4.9}$$

Starting with a fixed tau1 and a varying tau2 and 3 it can be seen in Figure 4.19 that the tax on intermediate sales method gives higher values for p1 and seems to show a non-linear response to increasing tax rates. The critical aspects to focus on here are the trends and not the absolute numbers, as this remains a hypothetical case.

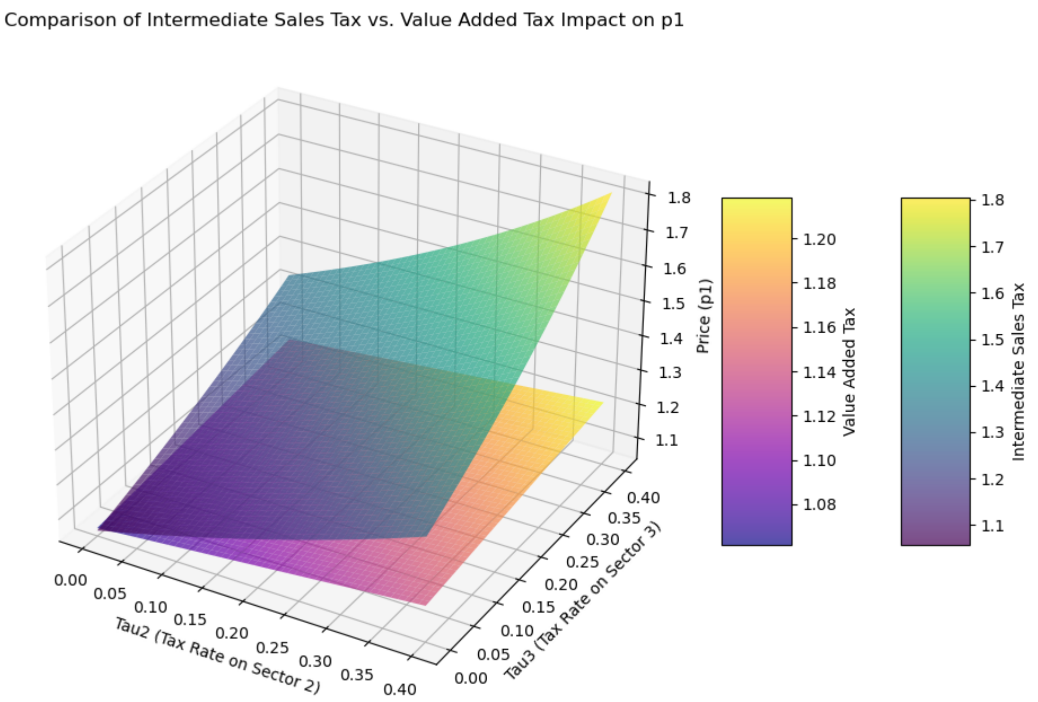


Figure 4.19: Three sector example where tau1 is fixed and tau2 and tau3 vary

Choosing a plane of this multi-variable plot, fixing tau 2, Figure 4.20 shows the way price varies between the two methods when only the third sector tax rate is varied. Hypothetically this third sector could be seen as the CBAM sector, and thus shows that when this third sector tax rate becomes non-zero - that is CBAM is implemented into the model - the intermediate sales method gives an increasingly higher result - the higher the sectoral tax rate the bigger the difference. Looking at the gradient of these lines,

Figure 4.21 shows that the intermediate sales method responds to increasing sectoral tax rates for a CBAM sector in a non-linear way, while the value-added tax method shows a linear response.

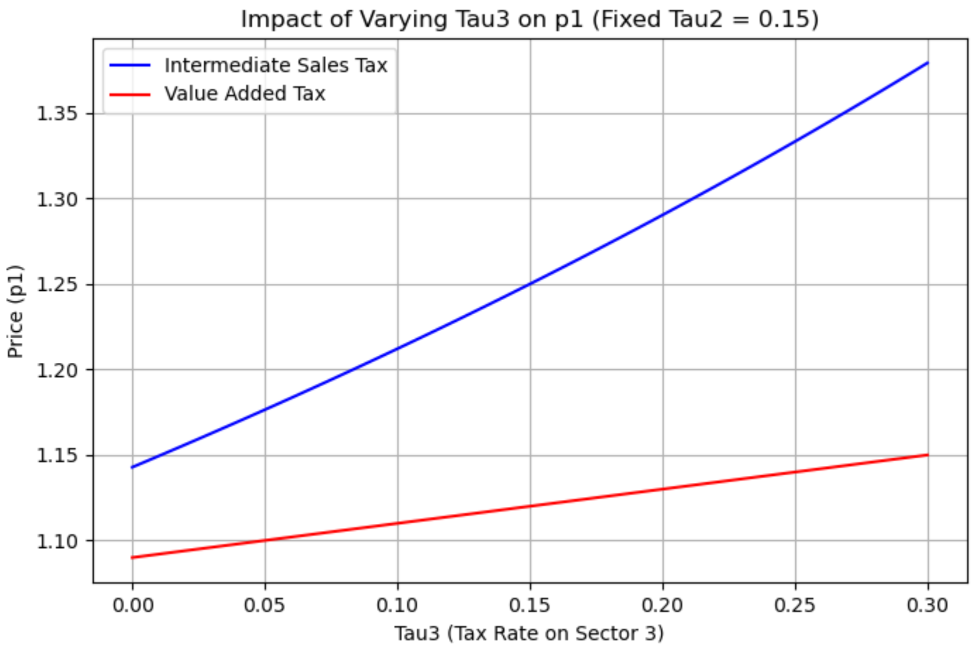


Figure 4.20: Three sector example where tau1 and tau2 are fixed and tau3 varies

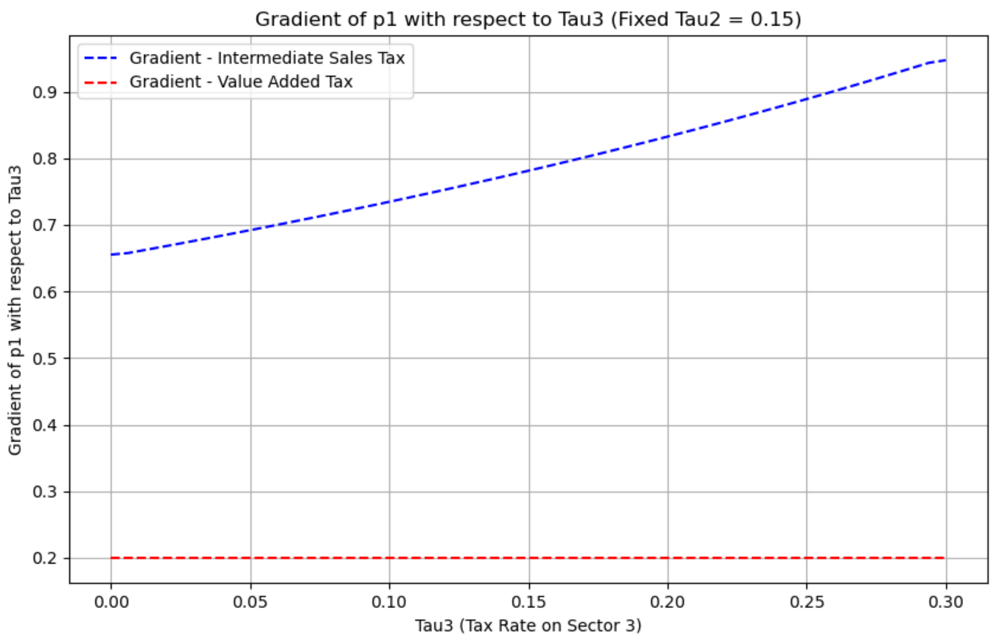


Figure 4.21: Gradient of both methods with respect to tau 3

SENSITIVITY TO THE STRUCTURE OF A

Lastly, to understand what might impact the differences in the two methods, the structure of the A matrix was varied. Three different A constructions were tested, one where the first two sectors were more dominant input sectors, one where all of the sectors contributed equally, and one where the last two sectors were dominant input sectors as can be seen below. For all scenarios, the value coefficient was kept the same.

$$A_{\text{low\_imports}} = \begin{bmatrix} 0.25 & 0.25 & 0.05 & 0.05 \\ 0.25 & 0.25 & 0.05 & 0.05 \\ 0.25 & 0.25 & 0.05 & 0.05 \\ 0.25 & 0.25 & 0.05 & 0.05 \end{bmatrix}$$

$$A_{\text{high\_imports}} = \begin{bmatrix} 0.1 & 0.1 & 0.2 & 0.2 \\ 0.1 & 0.1 & 0.2 & 0.2 \\ 0.1 & 0.1 & 0.2 & 0.2 \\ 0.1 & 0.1 & 0.2 & 0.2 \end{bmatrix}$$

$$A_{\text{equal\_imports}} = \begin{bmatrix} 0.15 & 0.15 & 0.15 & 0.15 \\ 0.15 & 0.15 & 0.15 & 0.15 \\ 0.15 & 0.15 & 0.15 & 0.15 \\ 0.15 & 0.15 & 0.15 & 0.15 \end{bmatrix}$$

To obtain these graphs below a similar process was followed where tau 1 and tau 2 were fixed and tau 3 and 4 were varied to produce a 3d plot. Then a cross-section was taken, fixing tau 3, and the following graphs were produced to see the impact of varying the 4th sectoral tax rate. The first interesting observation that can be seen in Figure 4.22 is that the changes in A matrix cause shifts up and down in the output price, where for this example specifically, intermediate sales yields a higher result; this may be specific to this hypothetical. When checking the gradient of these outputs in Figure 4.23, it can once again be seen that there is non-linearity in the intermediate sales methods. To provide some kind of context, it could be imagined that the last two sectors represent import sectors and the first two sectors represent domestic sectors.

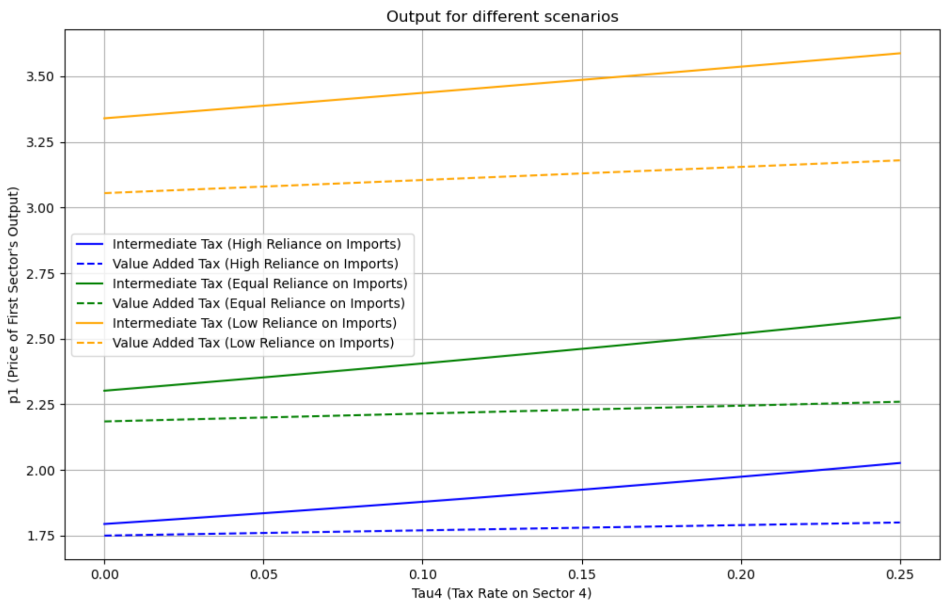


Figure 4.22: Three sector example where tau1 and tau2 are fixed and tau3 varies

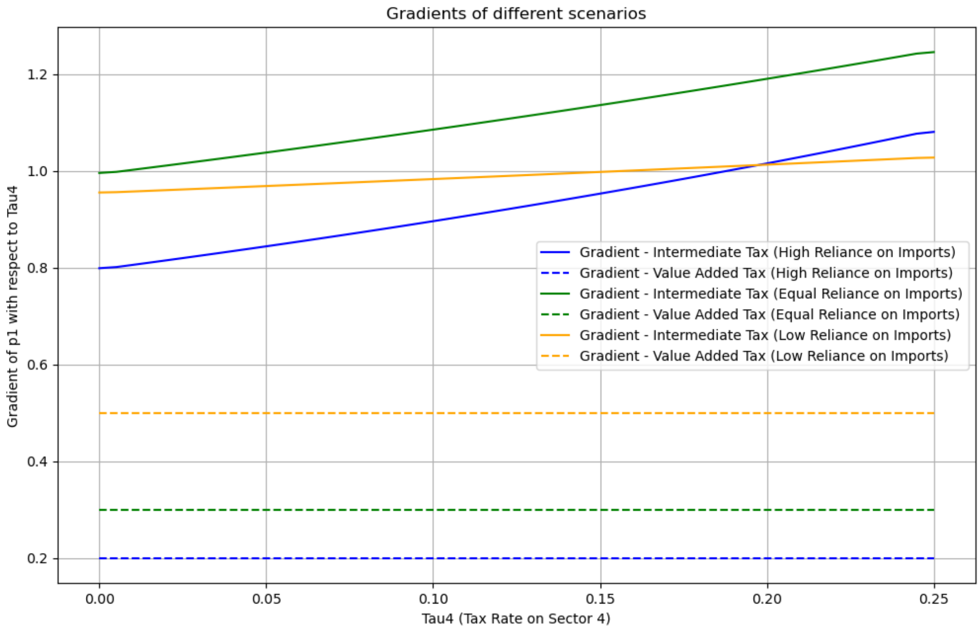


Figure 4.23: Gradient of both methods with respect to tau 3

MAIN TAKEAWAYS

Although these sensitivity analyses use hypothetical numbers, a few behaviours can be seen. Firstly, when more than two sectors are involved, the response of the intermediate sales method becomes non-linear. Secondly, the ratio of value coefficient and sectoral tax rates of the input sectors has an impact on which method gives higher results. Lastly, the composition of the A matrix—that is, how much each sector inputs to the output sector—impacts the price increase. One can understand the complexities of analyzing which parameters are dominant when expanded to the FGIARO data, which has an A matrix of 2944x2944 with different value coefficients and sectoral tax rates—this is extremely complex. That being said, this provides an initial insight into the differences between the two methods and forms the basis for further research.

## 4.3. LIMITATIONS OF THE MODEL

LIMITATIONS OF MODELLING CBAM

The way CBAM is implemented in the model is not a perfect representation of reality. There are limitations, and these have an impact on the results and thus should be discussed and analyzed. The method in which CBAM is implemented is explained in subsection 3.3.5. Several scenarios will be sketched to understand if CBAM is influencing results, and then conclusions will be drawn on what the impact is on the results.

Firstly, it is important to realize that the implementation of CBAM is from an EU perspective. In the model, a fictitious tax is being placed on CBAM sectors located in countries outside of the EU even if they do not have these themselves. This is simply how CBAM is modelled. However, this does not lead to any change in the results when analyzing the price effects. This means the model only accurately represents price effects when viewed from the EU's perspective, where all CBAM sectors become more expensive in proportion to their emissions. However, using this method, it is not possible to generate accurate data for absolute impacts on production prices outside of the EU.

Take the example of South Africa. In the current implementation, all CBAM sectors within South Africa are subject to a carbon tax at the same rate as the EU. In the model, a full carbon tax on CBAM sectors is just dropped onto the South African economy. This means that any exports to the EU are taxed, and the model provides accurate import prices for the EU. In reality, only a fraction of South African production is exported to the EU, and some is sold domestically. Domestic production prices in the model would all increase, as all of the CBAM sectors are taxed, whereas in reality, South African domestic trade is not taxed in the same way or at the same rate. To model the impacts of CBAM on extra-EU countries, the model would have to be heavily mathematically manipulated to apply tax only on exports. Due to the scope of this research being focused on price effects within the EU, doing this was not necessary.

The model overestimates price effects somewhat. What is not yet accounted for is whether carbon taxes have already been placed on the production in a country outside of the EU. In reality, if an importer can prove that a carbon tax has already been paid in an extra-EU country, this part of the embodied emissions is exempt from CBAM (Commission, 2024). This has not been accounted for in the model and could lead to double taxation in some countries, for example, in Canada, where a carbon tax is also implemented (Foundation, 2024). The impact on the results is that the price effect is overstated, and in reality, the impacts of the carbon tax and CBAM will be slightly lower. A recommendation for future research would be to account for different carbon mechanisms and prices around the world - this would add an extra layer of complexity to the model.

Two scenarios are illustrated below to demonstrate inaccuracies that may occur in the model. Starting with scenario 1, illustrated in Figure 4.24. Here a product is considered where all of the sectors in the supply chain are subject to CBAM. In this case, the model applies a tax to all of the sectors, and there is a price increase from sector 1 to 2 due to the carbon tax. Sector 2 then pays a tax on the emissions associated with its value-added, which increases the price further, and so on. When the good is then imported into the EU, represented by the dashed line, the price that is paid for this already accounts for all of the embodied emissions as all component sectors are CBAM. For products in this scenario, the model gives very accurate results and is neither over- nor understated.

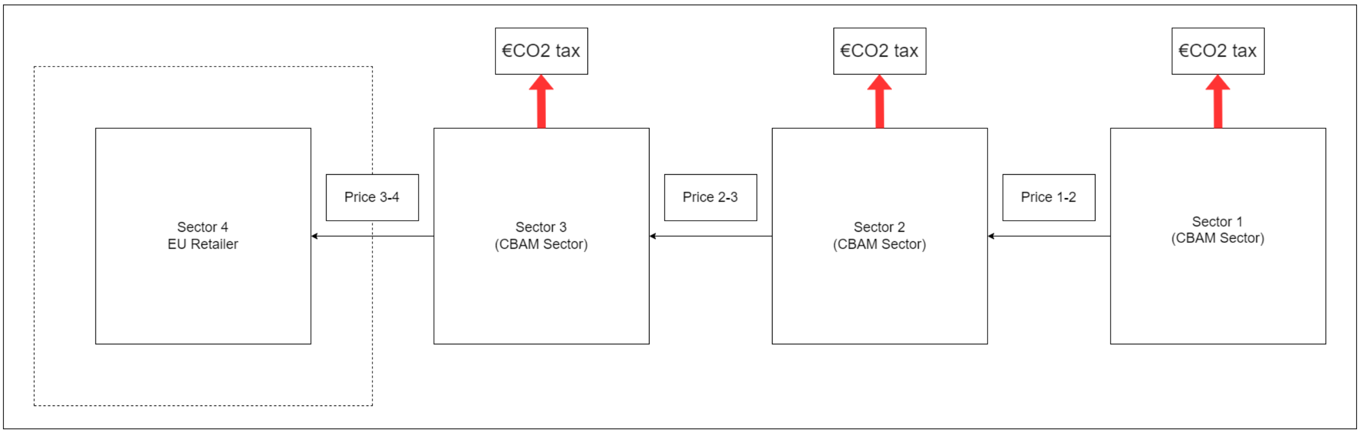


Figure 4.24: Scenario 1: CBAM on all sectors in supply chain outside of the EU

Scenario 2, as seen in Figure 4.25, can occur where the final product being imported from sector 3 is not a CBAM sector, for example, a car. The car and the manufacturing of that car are not subject to CBAM; however, the steel and aluminium used in its production are, which is further up the supply chain. The method implemented in the model accounts for this by ensuring that a tax is applied to CBAM sectors globally and not just at the point of crossing into the EU. Therefore in the model, a car door is more expensive than it would be in the model, as the car door is subject to CBAM in the model but currently not in reality. This represents an overestimation in the model compared to reality. The model is likely more accurate in for future set ups for CBAM as over the next decade CBAM sectors will be expanded.

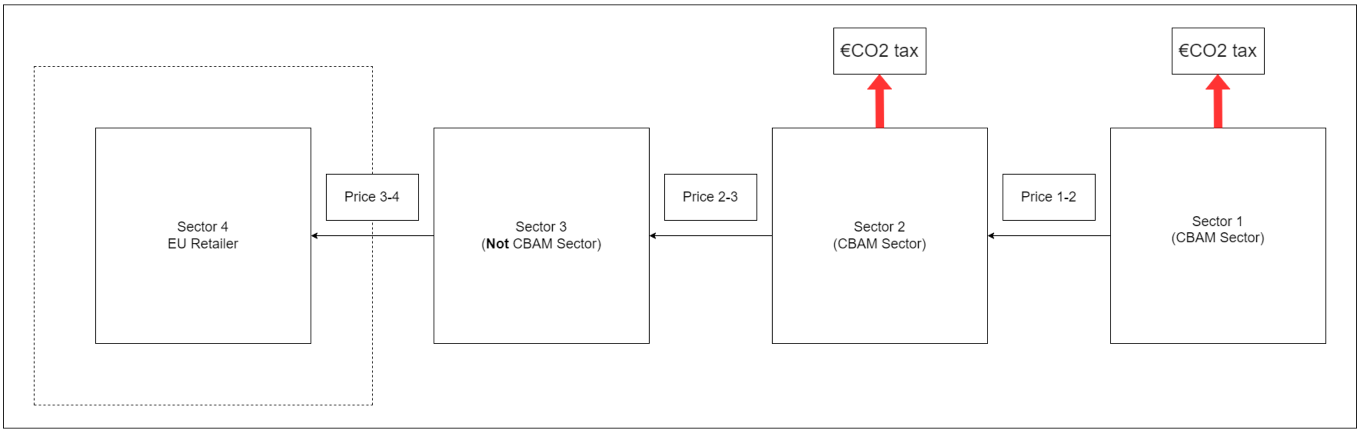


Figure 4.25: Scenario 2: CBAM only on early sectors in the supply chain

Currently, in CBAM regulations, scope 2 emissions are considered only for fertilizer, cement, and electricity. However, for simplicity, scope 2 emissions are considered for all CBAM sectors in this model, as electricity is always taxed, which aligns with the current view of scope 2 emissions. This means that the model slightly overestimates the impact, as scope 2 emissions for all CBAM sectors will only be included after the transitional period.

There are some limitations in how CBAM is modelled and these may result in slightly inaccurate results for the EU. Furthermore, the model takes a EU-centric perspective and does not accurately model non-EU countries. However, for this research, these limitations do not significantly negatively affect the results, though they do restrict the extent to which the model can be used for further analysis; namely extra-EU analysis. There is a risk of double taxation in countries that already have a domestic carbon tax, such as Canada, and this was not accounted for, which may lead to higher prices; thus, results, in reality, maybe more moderate. Lastly, scope 2 emissions are already considered for all CBAM sectors meaning in reality the effects will be slightly lower. After analysis of how CBAM is implemented in this model, it can be concluded that this model represents an overestimate and upper bound for the price effects of carbon policy and the effects in reality will be more moderate.

#### Assumptions

There are several key assumptions which are important to restate when interpreting the results. Firstly, the results seen here are in the context of a rigid economic structure, that is to say, there is no substitution here. In reality, decisions would be made on production techniques, different technologies or fuels rather quickly which would soften the blow of these price shocks. That means that price shocks in reality are lower than modelled. Additionally, many other factors impact prices of goods and flows in the economy, such as global oil prices and supply chain shortages. Lastly, reflecting on the data, the data does not differentiate between a Ford or Mercedes for example and therefore it is hard to draw specific conclusions. Although the FIGARO database is some of the best available data, different countries aggregate data in different ways and therefore there always remains some error even though this tries to be minimized.

## 4.4. Research in the context of existing literature

The most similar piece of research was done by Schotten et al. (2021) at De Nederlandsche Bank (DNB) in 2021 using 2015 data from a source with less granularity. The carbon price used there was 50 euros as opposed to the 70 euros used here, as the market price was lower in 2021. The results from the current model presented earlier in this chapter can be seen again in Figure 4.26, and is placed next to the results from a similar study which can be seen in Figure 4.27. Here scenario 1 and scenario 3 represent with and without CBAM respectively.

The results show similar orders of magnitude with almost the same distributional impacts. Key differences are that in the results of this paper, Poland is the most impacted country with Bulgaria second, whereas in the 2021 study, Poland is the third most impacted country. This could be due to a change in economic structure, but what is more likely is that it is because the DNB paper levies CBAM on the potential future expansion of CBAM, so to all ETS sectors. Another source of error could be how the different studies weighted the results or variations in how the sub-sectors were specifically grouped. The results calculated in this paper aim to show the impacts of the current implementation of CBAM. The result is that there is a slight difference in what imports are taxed; however, the difference is not large because the most carbon-intensive sectors are already covered in the current CBAM iteration.

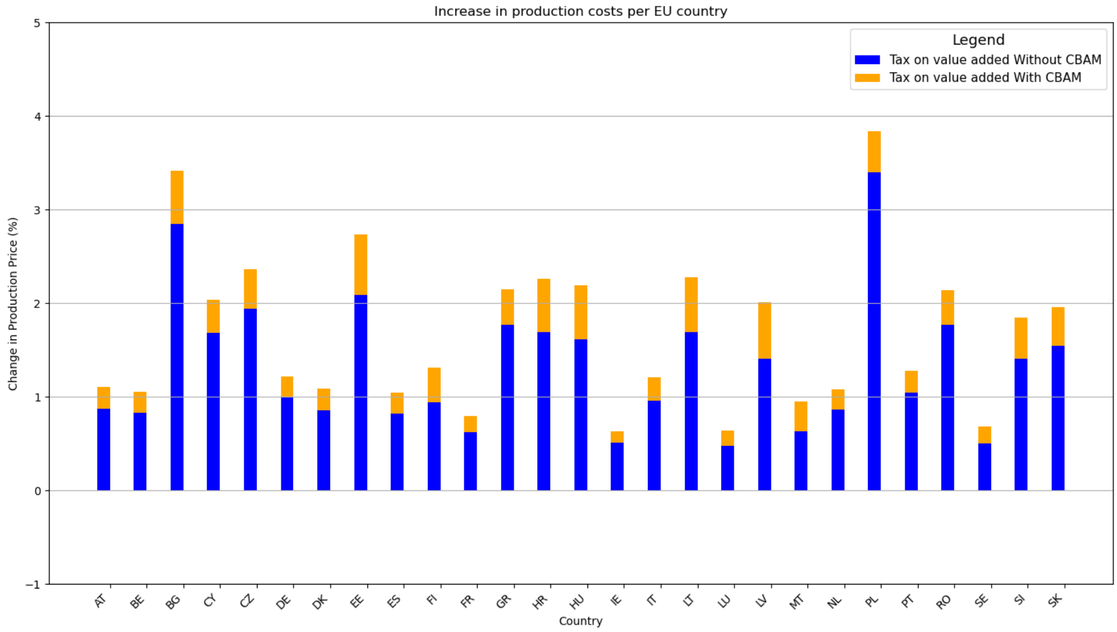


Figure 4.26: Results from current model with 70 euro carbon price

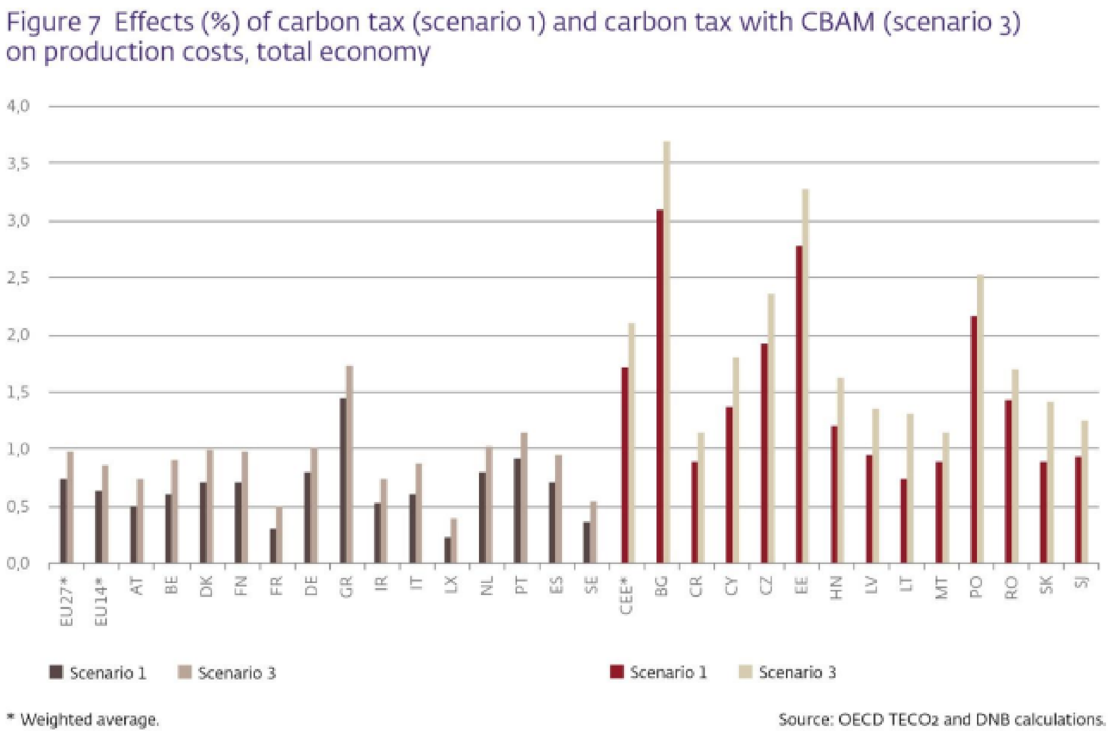


Figure 4.27: Results from 2021 study with 50 euro carbon price (Schotten et al., 2021)

Making this comparison and corroborating the order of magnitude and distributional effects builds out the quantity of literature present on this topic and contributes to building more accurate predictions of economic impacts in the EU due to carbon policy. Due to the granularity of the data used was not possible to make a like-for-like comparison on an industry level.

## 4.5. RESEARCH IN THE CONTEXT OF THE CARBON POLICY TIMELINE

The ETS directive has been a process that has been implemented in multiple phases throughout the last two decades, starting in 2005 (European Comission, n.d.-b). It began with low carbon prices in just a few sectors and progressively expanded to more sectors with new carbon prices and mechanisms to determine these prices. This leads to an important reflection on how the results in this chapter fit into that, as there are some important points.

The way the carbon tax was implemented in this model was to introduce a price shock of 70 euros/tonne for the EU carbon tax into the system. In reality, the carbon tax was already present in some sectors and at a lower price in 2021, which means for some sectors, the full additional exogenous input of an extra 70 euros per tonne of $CO_2$ is a larger increase than would be seen in reality as some of this tax is priced into the data. It was chosen to implement it this way due to the complexity of an ever-changing landscape of carbon prices and the sectors to which they applied. Doing it this way does allow for a fairer, more uniform analysis of how Europe would react to price shocks, albeit not fully accurate. The impact this has on the results calculated is that they are likely overestimated, and the impacts in reality will be somewhat smaller than calculated. The way CBAM is priced is in line with the real-time implementation of the policy.

## 4.6. RESEARCH IN THE CONTEXT OF WTO GOALS

The World Trade Organization is an important international body tasked with promoting the environment necessary for the free trade of goods across borders (WTO, 2024). In this thesis, competitiveness was primarily examined from the perspective of protecting EU interests and stopping carbon leakage, which is ultimately the goal of CBAM. However, it is essential to reflect on the results not only in that context but also within the broader trade climate. While a competitive advantage for the EU is beneficial for safeguarding EU interests and stopping carbon leakage, it also means that the global playing field is no longer level. Ideally, the competitive advantage or disadvantage would be neutral after the implementation of CBAM, such that the EU is not harmed by the carbon tax but also does not create uncompetitive situations for foreign firms. In some cases, competitive advantages for the EU arise after the introduction of CBAM. A more detailed analysis of CBAM pricing could be conducted to minimize competitive differences between EU and non-EU firms, though this varies significantly by industry. It is important to note, however, that CBAM's primary goal is not to create complete neutrality but rather to prevent carbon leakage and protect EU industries from unfair competition by countries with more lenient environmental policies. Finding a balance here is challenging and remains a point of discussion (Leal-Arcas et al., 2022).

## 4.7. IMPACT ON EXPORT VOLUMES

For extending the analysis to export volumes, the results of value-added were taken as these are more widely accepted in the context of existing literature. Competitiveness is considered from the perspective of the EU as described in section 4.3 and describes an EU economic actor choosing between purchasing from within the EU or outside the EU. It does not provide much insight into what would happen to the sales of EU actors who export. The use of trade elasticities can offer some indication, specifically the elasticities are Armington Coefficient of Substitution elasticities (CES). These elasticities are calculated by the World Bank and indicate, per country, the change in exports corresponding to a change in price (Devarajan et al., 2023).

Before analyzing the graph, it is important to understand the limitations of this analysis. To produce Figure 4.28, individual elasticities have been used. The results observed are those that would occur if the price increase was experienced by one EU country and not the others. This is because if all EU countries experience similar changes simultaneously, like an EU carbon policy, a new equilibrium will be found for intra-EU trade; however, this would require a very complex model to evaluate.

Simply put, if a hypothetical Dutch company purchases a product from France and the production price in France increases, but the price in other countries also goes up, there is not necessarily a better price to be found in other European countries, so trade volumes within the EU will likely remain relatively stable. This makes it particularly interesting to look at price elasticities concerning extra-EU exports, meaning exports from EU countries to places outside the EU. The analysis will be briefly outlined and explained.

The first step in the analysis was to use the elasticities and multiply them by the price increases derived from the input-output model. This provides results both with and without CBAM, as seen in Figure 4.28. This graph indicates that if any one country is considered on its own, the corresponding reductions in export volumes would occur. The countries hardest hit are Czechia, Estonia, Greece, and Poland, showing that any fluctuations in prices due to carbon pricing would result in a significant change in export volumes, in the order of 3% - 5%.

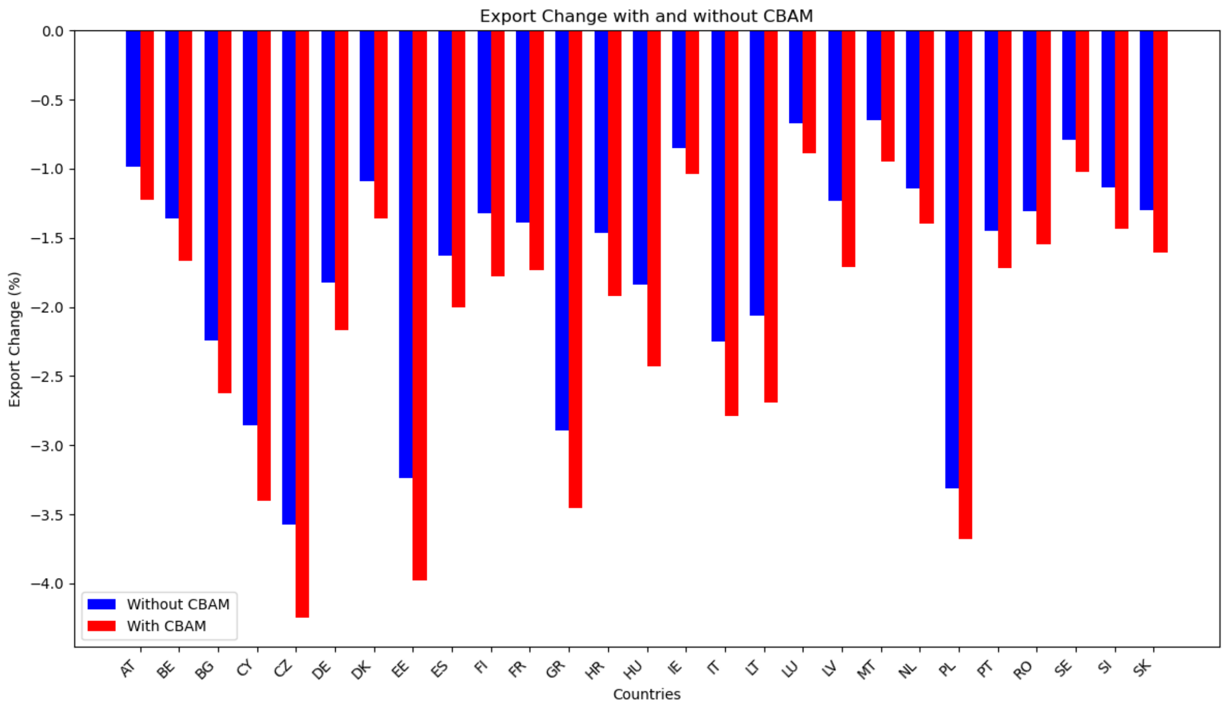


Figure 4.28: The change in export volumes due to increased production prices

The EU would find a new equilibrium regarding trading with each other. The extra-EU exports, meaning exports to countries outside of the EU, can be examined in more detail. The proportion of exports that go to countries outside of the eurozone can be seen in Figure 4.29. Please note that not all EU countries are represented here, as data is only compiled by Eurostat on eurozone countries for this specific topic. This graph immediately provides more insights into the export reliance of different economies.

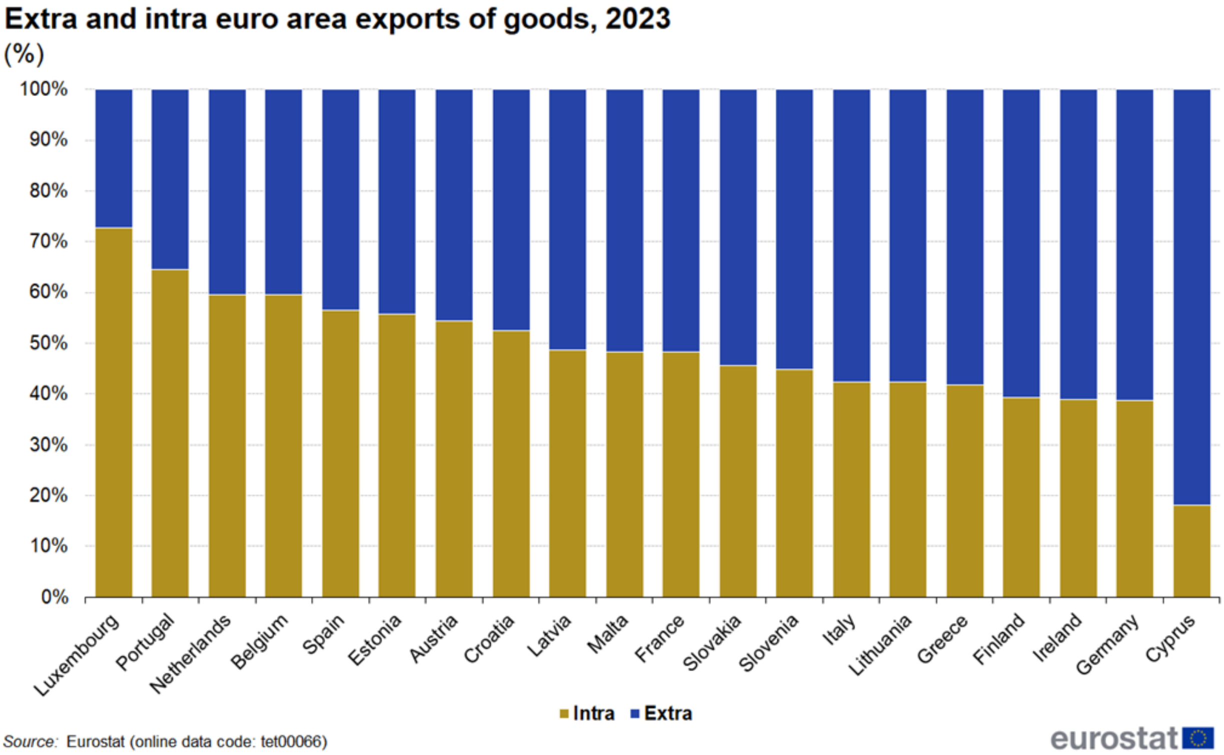


Figure 4.29: Intra vs Extra EU exports of Eurozone countries (Eurostat, 2024c)

Based on the export volumes and proportions an adjusted export change graph was made. This was normalized to take into account the proportion of extra-EU trade for every country. The assumption used here is that intra-EU trade does not change in volume with a carbon tax and CBAM, and only extra-EU trade decreases due to increased prices within Europe. The results can be seen in Figure 4.30.

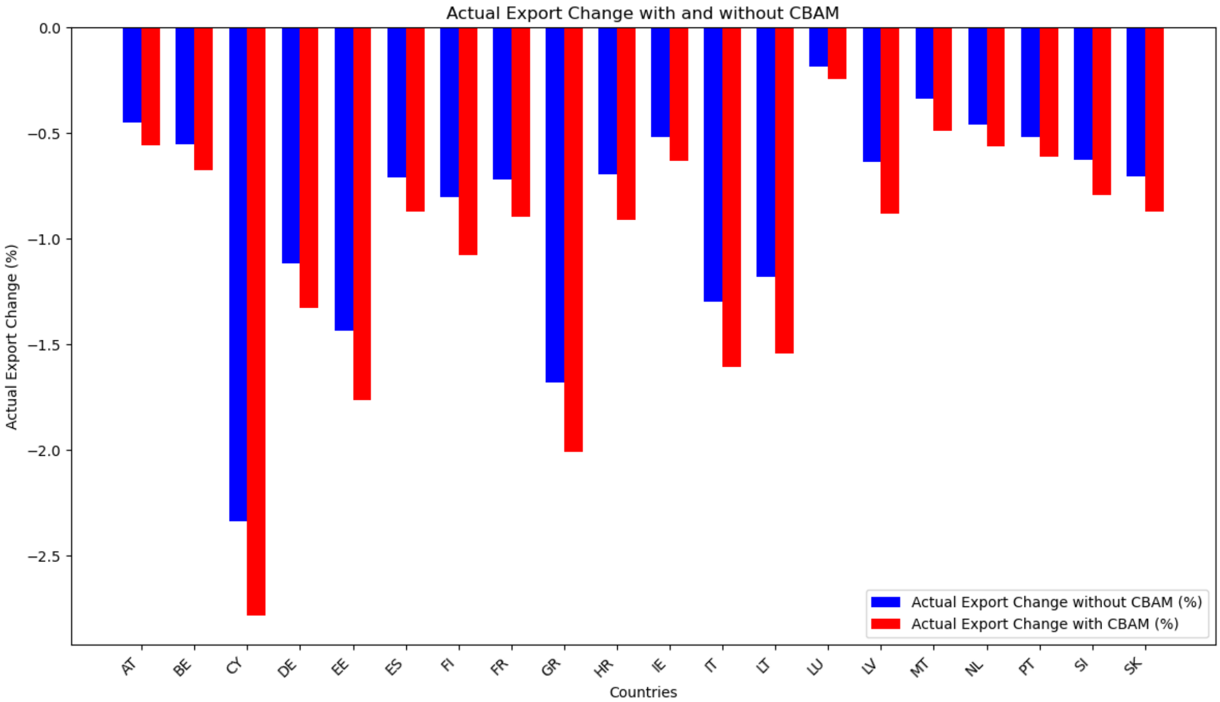


Figure 4.30: The actual change in export volumes due to increased production prices

Cyprus sees the largest impact of carbon policy, with its overall trade dropping by around 2.5%. This result is to be expected. As seen in Figure 4.29, 80% of Cyprus's exports leave the EU. A more surprising result is Estonia, whose overall drop in exports is over 1.5%, even though they export less than 50% of their goods outside the EU. This is likely due to the very high elasticity of trade in Estonia, meaning that small perturbations in prices can lead buyers to quickly choose other sellers. On average, a drop of around 0.5-1% can be seen in overall exports in the eurozone.

This analysis gives an insight into the order of magnitude of export reduction due to carbon policy; however, it remains a rough estimate as complicated general equilibrium models are needed to calculate this accurately. Computational equilibrium models take into consideration the theoretical behaviour of different economic actors. The economy is modelled, and a change can be implemented, such as a carbon tax. The key difference from input-output modelling is that here the profit-maximizing behaviour of firms is modelled, the utility-maximizing behaviour of households is modelled, and substitution occurs, meaning economic actors will change methods and techniques based on economic circumstances. The model attempts to solve all of these different behaviours and price functions to a point where economic equilibrium is met again (Böhringer et al., 2003). This more accurately describes the economy but is more complex and computationally intensive.

Reflecting on trade with non-EU countries after the implementation of an EU carbon policy the hypothetical example of China can be used. In the context of exports, China's production prices will also increase, as they use inputs from Europe, which have knock-on effects on EU prices and import choices. The behaviours are not arbitrary and require more research and analysis.

## 4.8. POLITICAL ECONOMY & EFFECTIVENESS IN THE ENERGY TRANSITION

Zooming out on what price effects mean for the wider political economy and what it means for the effectiveness of stimulating an energy transition is critical to reflect upon. Firstly, what it costs, the impact on employment, public acceptance and potential WTO issues will be discussed. The distributional impacts will then be discussed both within and outside of Europe as well in-direct costs Europe could face from ineffective carbon policy. Lastly, an attempt will be made to place the price increases calculated into the broader energy transition.

CBAM is a relatively complex and political EU instrument designed to protect EU interests as well as stimulate the energy transition abroad. Looking at distributional impacts across Europe that have been calculated in chapter 4, Eastern European countries generally suffer more from the implementation of regulation, and it is therefore not surprising that these countries initially resisted these policies more. When breaking this down further, and looking at public support for CBAM, it is approximately 10% higher for CBAM than it was for a national carbon tax due to the measure protecting domestic interests (Bayer and Schaffer, 2024). This is coupled with the risk of carbon taxes and CBAM potentially being somewhat regressive, as they impact poorer households relatively more than richer households. This still needs to be supported by empirical evidence, although it can be mitigated through effective revenue recycling options (Callan et al., 2009). Another potential reason for lower acceptance of carbon pricing is the impact on exports, as estimated in section 4.7. Extra-EU exports support 14.5% of jobs in the EU, and any risk to this may cause pushback against the policy. Naturally, there is also a distributional impact on the reliance on extra-EU imports, and countries such as Ireland, Luxembourg, Cyprus, and Denmark are impacted the most, as can be seen in Figure 4.31.

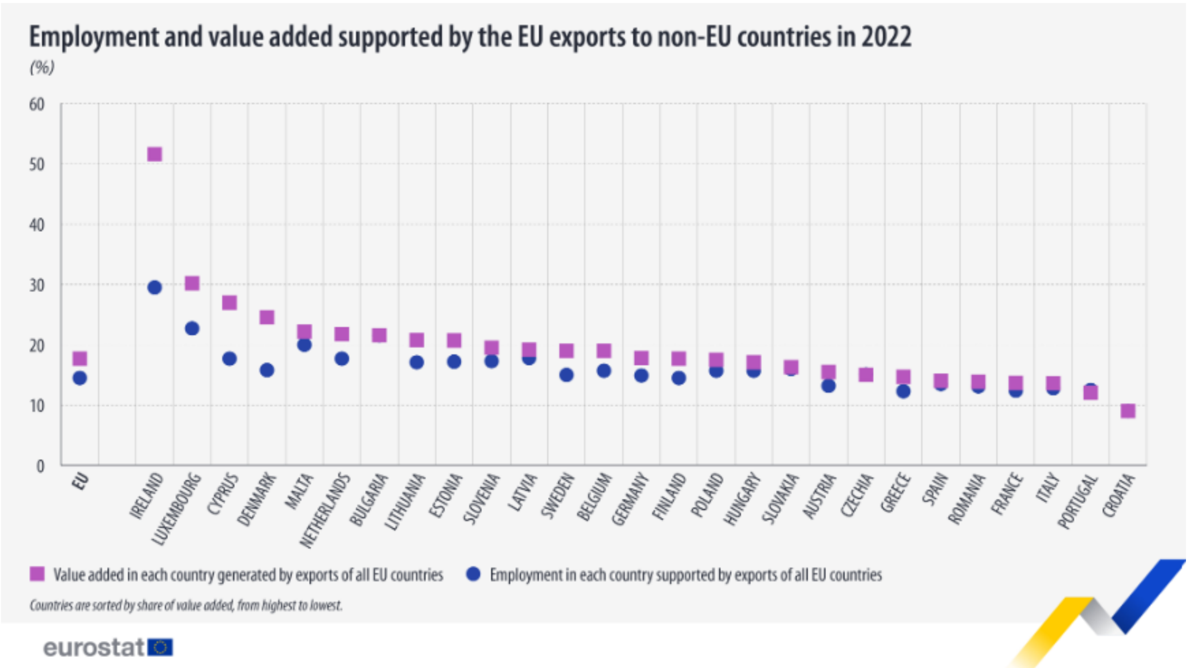


Figure 4.31: Importance of exports to EU countries (Eurostat, 2024b)

Extending the analysis on the distributional impacts of carbon pricing and CBAM to countries outside of the EU, both positive and negative effects can be seen. According to Pauw et al. (2022), there have already been positive effects on trading partners of the EU by stimulating them to implement a carbon pricing mechanism of their own. Turkey is a good example of this and reinforces the effectiveness of CBAM as a foreign policy tool. On the flip side, the analysis also highlights the potential negative impact on vulnerable or developing economies by not allowing them to industrialize traditionally. However, this ensures that these countries are not seen as "last movers", meaning they will not get left behind in the energy transition and hopefully can use their position as an advantage (Pauw et al., 2022). It is therefore essential that the implementation of CBAM is done predictably and gradually to allow developing countries — analyses show mainly African countries — to transition in time. Eicke et al. (2021) stresses that capacity building of technologies in developing countries is also paramount to protecting

EU interests. There are also non-financial incentives to work on capacity building and help reduce trading partners' emissions. Developing countries are likely to suffer the most from the negative weather effects of climate change (Hugo, 2011). Currently, 21.5 million people are displaced every year, and by 2050 models have shown that over 1.2 billion people could be displaced due to extreme weather associated with climate change. Not only is this extremely negative for the safety and preservation of life of the affected populations, but it also brings a financial cost to countries where weather events are less extreme, such as Europe, where migrants will seek refuge. The potential cost of dealing with extreme weather events in Europe alone could be 145 billion euros (Forum, 2022), and the additional costs from migration add to this. This puts the calculated 1.26% increase in production price, calculated in this thesis, in perspective as a necessary measure to prevent this from happening.

A prominent discussion around CBAM has been issues on the legal and administrative side. During the development of CBAM, there were queries by members of the WTO, mainly from BRICS countries, that it would violate free trade agreements and risk starting trade wars, driving prices up further. Most of these concerns have been addressed during the development process, and opposition has generally subsided as other countries have started implementing similar measures. The WTO has also started considering extra rules specifically around the trading of carbon-intensive goods, so these developments should be monitored closely. To ensure no major issues arise again, the predictable implementation of CBAM with high levels of international cooperation is needed (Leal-Arcas et al., 2022). Furthermore, a large administrative burden comes with the implementation of CBAM, including reporting embodied emissions and ensuring no fraud occurs. This burden is significant but should not discourage implementation, as solutions can be found by conducting checks at a firm level rather than at the border, as well as using some of the CBAM revenue to streamline the administrative process and remove barriers (Pauwelyn, 2024).

The effectiveness of carbon pricing in stimulating a transition to sustainable energy technologies still remains a theoretical conclusion. There is little empirical evidence to support the notion that carbon pricing increases investment into the development of cleaner technologies (Lilliestam et al., 2021). This is, however, largely due to lower carbon prices from the last two decades, and one case study does provide support for the claim that it is effective. Sweden implemented one of the earliest carbon taxes in 1991, at 139 euros per tonne, and saw a decrease of 16% in emissions from 2000-2012 while experiencing GDP growth of 30%. This shows that higher carbon prices do correlate with decreased emissions and do not necessarily cause recessions (Newman, 2021). A counter-explanation to this is that these changes to cleaner technologies would have been made anyway for cost-saving, so a real stream of empirical data still needs to present itself. Lilliestam et al. (2021) argues that other factors play an important role in the transition to cleaner technologies, which must occur in parallel with increasing carbon prices for effective investment into cleaner technologies. Support programs, as well as investing in infrastructure and market mechanisms are needed for newer technologies to flourish. Additionally, markets and infrastructure are currently built around fossil fuels and so investment into updating this is essential. Diffusing R&D progress to developing countries also remains imperative. Combining a carbon tax with non-price factors, as well as subsidies, is part of a holistic solution that has shown encouraging impacts on emissions reductions and investment into clean technology (Lilliestam et al., 2021). This is also in line with the theory of Functions of Innovation Systems (FIS), which dictates that for new technology systems to be successful, multiple different functions must work together in order for this to happen (Kamp, 2008). Namely, knowledge diffusion, market formation & guidance of search are very topical as they relate to sharing R&D and investing in capacity building in developing countries, investing in infrastructure and markets for new technologies to be successful, as well as good guidance from the government on clean energy, emissions targets and the roadmap to these targets. According to Lilliestam et al. (2021), political investment is very high in ETS and CBAM, and therefore it is unlikely that the lack of empirical evidence will lead to this approach being abandoned. However, it should be combined with other policy measures and initiatives to effectively promote investment into renewable technologies. Lastly, carbon tax and CBAM present a great way to generate revenue for these other measures and fit into the broad approach.

## 4.9. PRACTICAL IMPLICATIONS

The findings of this thesis lead to several practical implications for governments, firms, and international organizations. These implications outline the key actions necessary to implement effective carbon policies and facilitate the transition to a low-carbon economy.

### 4.9.1. NATIONAL GOVERNMENT ACTIONS

National governments play a crucial role in ensuring the success of carbon policies. One immediate priority should be the implementation of revenue recycling mechanisms. These mechanisms can be used to support industries most affected by carbon pricing, particularly those at risk of carbon leakage, thereby ensuring a smoother transition. Governments should also prioritize significant investments in workforce training, particularly for sectors expected to undergo substantial technological change and those that rely heavily on exports. On a European level, targeted revenue recycling and investment should focus on Eastern European countries, which are most impacted by carbon policies. This should be accompanied by strong parallel investments in infrastructure and R&D to position Europe as a global leader in the green economy. Additionally, subsidies must be provided strategically, with the U.S. Inflation Reduction Act serving as a valuable example of how to stimulate green investments without causing undue economic disruption.

### 4.9.2. PRIVATE SECTOR ACTIONS

Private companies should use the transitional period to green their supply chains and establish efficient carbon accounting systems. This will ensure that firms are well-prepared when the transition period ends and when potential scope expansions are introduced.

### 4.9.3. INTERNATIONAL ACTIONS

At the international level, the WTO should focus on standardizing carbon policies across countries to create a level playing field and reduce administrative burdens on international trade. Other organizations, such as the European Commission and the United Nations, should emphasize capacity building in developing countries. This will help ensure that these countries are not "last movers" in the energy transition and mitigate the risks associated with climate-induced migration.

# 5 | Conclusion & Recommendations

## 5.1. Conclusion

Carbon policy is constantly evolving and understanding the price effects of carbon tax and CBAM is imperative for identifying economic impacts such as price increases and changes in competitiveness, which relate to carbon leakage and by extension the effectiveness of carbon tax in meeting climate goals. An analysis carried out of current literature on price effects of carbon policy showed that there is: limited research with up-to-date and high granularity data, few studies which shed light onto sector-specific impacts, and a lack of diversity in methods which mainly use computational equilibrium analysis. To fill this knowledge gap input-output modelling and highly granular 2021 data were used. The carbon tax was applied through on value-added - which is standard practice - as well on intermediate sales which is more novel. This led to the main research question: "What are the price effects of carbon policy?"

To answer this question the method of tax on value added was used first as this is the most commonly applied method in literature. This showed that the weighted average production prices of the EU on average increased by 1.26% with carbon tax and CBAM, and CBAM itself changed a competitive disadvantage of -0.98% to a 1.46% competitive advantage. This suggests that CBAM is effective in protecting the EU's competitiveness and increases in production prices remain moderate on average. Distributional analysis showed that amongst EU countries, generally Eastern European countries are worst hit by carbon tax and CBAM due to a relatively large proportion of the economy being comprised of agriculture and mining & quarrying which are emission-intensive processes. Here the most extreme price increase was 3.84% in Poland. Eastern European countries also experienced the highest increases in production prices purely due to the implementation of CBAM on top of the existing carbon tax due to their reliance on carbon-intensive imports. Additionally, the results were used to estimate the decrease in export volume for eurozone countries and this was found to be between 1.5-2%.

With respect to sector-specific analysis, it was found that the electricity and gas sector was hit heavily, across EU industries, seeing a total price increase of 10.10% under carbon tax and CBAM, with the next two most impacted sectors being mining & quarrying, agriculture, and transport. These sectors experienced price increases of around 2% on average. While the introduction of CBAM generally protected all EU industries from competitive disadvantages, manufacturing and transport still experienced disadvantages. This is especially concerning as manufacturing is a sector that has seen significant offshoring over the last two decades. Breaking down the manufacturing sector further, the main subsector that faced a negative disadvantage was coke & refined petroleum products; this sub-sector faces an increased risk of carbon leakage due to production outside of the EU and then importing still being cheaper.

The input-output model is not without limitations. Due to the way CBAM was implemented, any absolute results of production prices in non-EU countries are invalid. This is firstly because, the results produced by the model are based on what the EU sees as the non-EU prices, behind an import-tariff wall. If non-EU countries exported 100% of their goods to the EU, then the model would be accurate, but this is not the case. The model therefore only provides accurate information on the price effects in the EU. Secondly, the measure of competitiveness is price competitiveness as seen from an EU firm. The definition of competitiveness is therefore: the difference in price for an EU firm when choosing to purchase a good from another EU firm compared to a non-EU firm. It does not therefore give insight into competitiveness from the perspective of non-EU firms. This model further does not take carbon taxes already present in countries of origin into consideration, which would exempt importers from paying the full CBAM. Therefore, the model slightly overestimates the price shocks. When looking at the timing of this thesis, a tax increase of 70 euros per tonne of carbon dioxide was introduced and thus the results are based on this price shock. However, in reality, the carbon tax in the year of the data – 2021 - was already non-zero therefore some carbon tax is already incorporated. This means that the results in this model likely carry a significant overestimation of the negative impacts.

Tax on intermediate sales is not a commonly used method when evaluating the price effects of carbon policy, yet the method is outlined in literature. To add to existing literature and compare this method to the value-added method, the tax on intermediate sales method was also employed. The results of the two methods were generally similar, although the price impact of introducing CBAM was much more pronounced in the intermediate sales method. When performing a sensitivity analysis it revealed that as more sectors are involved, the intermediate sales method becomes non-linear, and the value coefficient and sectoral tax rates influence which method yields higher results. Additionally, the structure of the A matrix significantly affects price increases, highlighting the complexity when applied to larger datasets like FGIARO. While this does not fully explain the results, the sensitivity analysis does give some insight into the variables that impact them and warrant further research.

Zooming out to the political economy carbon policies, a few interesting conclusions can be drawn, with respect to key stakeholders. A key finding is that public acceptance of CBAM is 10% higher than of the initial carbon tax, likely due to it protecting domestic interests. Furthermore, due to Eastern European countries being most impacted by carbon policies, there is more significant resistance from these countries, so capacity-building tools and revenue-recycling policies should be considered to lessen this impact. The impact on trade partners is both positive and negative. To mitigate the negative impacts, it is important to implement CBAM predictably and steadily while focusing on capacity-building tools with developing countries. Additionally, an attempt should be made to streamline the administrative hurdles that will be incurred using a portion of the CBAM revenues. With respect to the effectiveness of carbon pricing in stimulating sustainable energy technologies, there is limited empirical evidence to suggest a correlation. This is likely due to low carbon prices as Sweden has proven that with high carbon prices, emissions can be reduced without negatively impacting GDP. Where greater success in innovation has been seen is when carbon tax is combined with support programmes, subsidies, investment into the market design as well as effective diffusion of R&D.

The use of newer and high-granularity data, as well as diversifying methodology with respect to computational equilibrium analysis in this thesis, builds on existing literature as well as provides a novel comparison of two input-output models on carbon policy: tax on value-added and tax on intermediate sales. This comparison requires further research to expand on the mechanics of each of the methods. The methodology should also be developed to be able to give accurate results for non-EU countries, and altered to take into account the existing carbon market mechanisms in other countries in order to provide more accurate estimates of price effects. The research therefore provides an excellent framework to expand analysis on carbon taxation and CBAM and help inform policy decisions around the energy transition.

## 5.2. FUTURE RECOMMENDATIONS

This thesis forms the basis for future research, and several recommendations are drawn from the insights generated. Starting from the model's limitations, there are multiple areas where it could be expanded.

First, due to the way the CBAM is implemented, the model is inaccurate for understanding the price effects experienced outside the EU. The model could be improved by only applying the CBAM to EU-destined exports, which would allow an analysis of the effects of EU carbon policies on trade partners.

Secondly, the model introduces a fully exogenous price increase of 70 euros per tonne of $CO_2$ across all sectors. This is an overestimate because the 2021 data used already incorporates some sector-specific carbon taxes, albeit at lower carbon prices. This is a complex issue, as 2021 marked the end of Phase 3 of the EU ETS, during which substantial free allocation still existed and not all sectors were covered. A model improvement could involve assigning a tailored exogenous carbon price per sector, depending on 2021 coverage, carbon price, and free allocation. Since the results in this thesis describe an upper bound, more accurate outcomes could be obtained by refining this price increase.

Furthermore, when implementing the CBAM, foreign carbon markets were not considered. For instance, Canada has its own carbon market, and in theory, imports from Canada should be exempt from some portions of the CBAM, as a tax has already been levied on the embodied emissions. This aspect is not accounted for in the model, raising the risk of double taxation on emissions. A recommendation for future research is to incorporate such pricing considerations into the model to improve accuracy.

Another limitation is the definition of competitiveness, which adopts an EU-centric perspective, focusing on the decision of an EU firm to buy from either an EU or non-EU firm. This definition is confined to price competitiveness, while other dimensions could be explored, such as export competitiveness and the impacts on export volumes. Additionally, the price increases were weighted by value-added, though other weighting options, such as total output, employment, or export volumes, could also be explored to provide a more holistic view.

When comparing the intermediate sales method with the value-added method, it is important to further investigate the mechanics of the model through extensive sensitivity analyses to determine which method is more accurate under various scenarios. Moreover, the concept of cascading sales tax, discussed in the literature (Shome, 1995), warrants further analysis to better understand its occurrence in the intermediate sales method.

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# A | FIGARO Data Breakdown

## A.1. FIGARO SECTOR BREAKDOWN

Table A.1: FIGARO Industries and Sectors

| Industry Code | Industry | Sector Code | Sector |
|---|---|---|---|
| A | Agriculture, forestry and fishing | | |
| | | A01 | Crop and animal production, hunting and related service activities |
| | | A02 | Forestry and logging |
| | | A03 | Fishing and aquaculture |
| B | Mining and quarrying | | |
| C | Manufacturing | | |
| | | C10T12 | Manufacture of food products; beverages and tobacco products |
| | | C13T15 | Manufacture of textiles, wearing apparel, leather and related products |
| | | C16 | Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials |
| | | C17 | Manufacture of paper and paper products |
| | | C18 | Printing and reproduction of recorded media |
| | | C19 | Manufacture of coke and refined petroleum products |
| | | C20 | Manufacture of chemicals and chemical products |
| | | C21 | Manufacture of basic pharmaceutical products and pharmaceutical preparations |
| | | C22 | Manufacture of rubber and plastic products |
| | | C23 | Manufacture of other non-metallic mineral products |
| | | C24 | Manufacture of basic metals |
| | | C25 | Manufacture of fabricated metal products, except machinery and equipment |
| | | C26 | Manufacture of computer, electronic and optical products |
| | | C27 | Manufacture of electrical equipment |
| | | C28 | Manufacture of machinery and equipment n.e.c. |
| | | C29 | Manufacture of motor vehicles, trailers and semi-trailers |
| | | C30 | Manufacture of other transport equipment |
| | | C31_32 | Manufacture of furniture; other manufacturing |
| | | C33 | Repair and installation of machinery and equipment |
| D | Electricity, gas, steam and air conditioning supply | | |
| E | Water supply; sewerage; waste management and remediation activities | | |
| | | E36 | Water collection, treatment and supply |
| | | E37T39 | Sewerage, waste management, remediation activities |
| F | Construction | | |
| G | Wholesale and retail trade; repair of motor vehicles and motorcycles | | |
| | | G45 | Wholesale and retail trade and repair of motor vehicles and motorcycles |
| | | G46 | Wholesale trade, except of motor vehicles and motorcycles |
| | | G47 | Retail trade, except of motor vehicles and motorcycles |
| H | Transporting and storage | | |
| | | H49 | Land transport and transport via pipelines |
| | | H50 | Water transport |
| | | H51 | Air transport |
| | | H52 | Warehousing and support activities for transportation |
| | | H53 | Postal and courier activities |
| I | Accommodation and food service activities | | |
| J | Information and communication | | |
| | | J58 | Publishing activities |
| | | J59$_6$0 | Motion picture, video, television programme production; programming and broadcasting activities |
| | | J61 | Telecommunications |
| | | J62$_6$3 | Computer programming, consultancy, and information service activities |
| K | Financial and insurance activities | | |
| | | K64 | Financial service activities, except insurance and pension funding |
| | | K65 | Insurance, reinsurance and pension funding, except compulsory social security |
| | | K66 | Activities auxiliary to financial services and insurance activities |
| L | Real estate activities | | |
| M | Professional, scientific and technical activities | | |
| | | M69$_7$0 | Legal and accounting activities; activities of head offices; management consultancy activities |
| | | M71 | Architectural and engineering activities; technical testing and analysis |
| | | M72 | Scientific research and development |
| | | M73 | Advertising and market research |
| | | M74$_7$5 | Other professional, scientific and technical activities; veterinary activities |
| N | Administrative and support service activities | | |
| | | N77 | Rental and leasing activities |
| | | N78 | Employment activities |
| | | N79 | Travel agency, tour operator reservation service and related activities |
| | | N80T82 | Security and investigation, service and landscape, office administrative and support activities |
| O | Public administration and defence; compulsory social security | | |
| P | Education | | |
| Q | Human health and social work activities | | |
| R | Arts, entertainment and recreation | | |
| | | R90T92 | Creative, arts and entertainment activities; libraries, archives, museums and other cultural activities; gambling and betting activities |
| | | R93 | Sports activities and amusement and recreation activities |
| S | Other services activities | | |
| | | S94 | Activities of membership organisations |
| | | S95 | Repair of computers and personal and household goods |
| | | S96 | Other personal service activities |
| T | Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use | | |
| U | Activities of extraterritorial organisations and bodies | | |

## A.2. BREAKDOWN OF FINAL DEMAND

An overview of the breakdown of final demand is given in Table A.2.

Table A.2: Overview of components of final demand

| FIGARO label | Description |
|---|---|
| P3_S13 | Government consumption |
| P3_S14 | Household consumption |
| P3_S15 | Non-Profit Institutions Serving Households (NPISH) consumption |
| P51G | Gross fixed capital formation |
| P5M | Changes in valuables and inventories |

The aggregated demand per sector is then given by Equation A.2. For simplicity, throughout most of the model, the aggregated demand is used, as this is sufficient to analyse price effects.

$$f_i = P3\_S13_i + P3\_S14_i + P3\_S15 + P51G + P5M \tag{A.1}$$

## A.3. BREAKDOWN OF VALUE ADDED

For every sector, there is a value added to the economy which is, in a similar way to final demand, broken down into subcategories. These sub-categories are stated in Table A.3.

Table A.3: Overview of components of value added

| FIGARO label | Description |
|---|---|
| B2_A3G | Gross operating surplus |
| D1 | Compensation of employees |
| D21X31 | Taxes less subsidies on products |
| D29X39 | Other net taxes on products |
| OP_NRES | Purchases of non-residents in the domestic territory |
| OP_ RES | Direct purchase abroad by residents |

Similarly to final demand, the aggregation of value added can be done as follows:

$$v_j = B2\_A3G_j + D1_j + D21X31_j + D29X39_j + OP\_NRES_j + OP\_RES_j \tag{A.2}$$

# B | Derivations

## B.1. Core matrix equation derivation

In Equation B.1, the example of a single sector is taken. For ease of explanation, this sector is assumed to be the steel sector. The total output of the steel sector is then equal to the flows to other sectors, for example to itself, to the automotive sector, and to the construction sector represented by the Z variables as well as the final demand for steel by end consumers, given by $f$.

$$x_1 = z_{11} + z_{12} + z_{13} + ... + z_{1j} + f_1 \tag{B.1}$$

Equation 3.2 can be expanded to all of the sectors, so every sector's total output can be mathematically described as what it sells to other sectors - known as intermediate sales - as well as what it sells to the economy in final demand. This leads to a set of equations as follows:

$$\begin{aligned} x_1 &= z_{11} + \cdots + z_{1j} + \cdots + z_{1n} + f_1 \\ &\vdots \\ x_i &= z_{i1} + \cdots + z_{ij} + \cdots + z_{in} + f_i \\ &\vdots \\ x_n &= z_{n1} + \cdots + z_{nj} + \cdots + z_{nn} + f_n \end{aligned} \tag{B.2}$$

This is then put into matrix form. This matrix form comprises several sub-matrices that can be seen in Equation B.3. Firstly, the **x** is a column vector of all the total outputs for every sector. Secondly, the **Z** matrix represents all of the intermediate sales between sectors, and **f** is a column vector which is the final demand from all sectors to the economy.

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} Z_{11} & \dots & Z_{1n} \\ \vdots & \ddots & \vdots \\ Z_{n1} & \dots & Z_{nn} \end{bmatrix}, \mathbf{f} = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \tag{B.3}$$

Using these building blocks Equation B.2 can be then written in matrix form which leads to Equation B.4.

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} Z_{11} & \dots & Z_{1n} \\ \vdots & \ddots & \vdots \\ Z_{n1} & \dots & Z_{nn} \end{bmatrix} \cdot \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} + \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \tag{B.4}$$

Using matrix notation this can further be generalised into a matrix equation in Equation B.5 where **i** is a vector of 1s.

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f} \tag{B.5}$$

## B.2. TECHNICAL COEFFICIENT & LEONTIEF DERIVATION

To calculate the technical coefficients of the Z matrix, all of the outputs are needed. This is done by vertically summing along a sector j in the IO table. Then Equation B.6 can be defined.

$$\hat{\mathbf{x}} = \begin{bmatrix} x_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & x_n \end{bmatrix}, \tag{B.6}$$

This can then be multiplied with the intermediate sales in order to calculate the technical coefficients as can be seen in Equation B.7.

$$\mathbf{A} = \mathbf{Z} \cdot \hat{\mathbf{x}}^{-1} \rightarrow \mathbf{A} = \begin{bmatrix} \frac{Z_{11}}{x_1} & \dots & \frac{Z_{1n}}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{Z_{n1}}{x_1} & \dots & \frac{Z_{nn}}{x_n} \end{bmatrix} \rightarrow \mathbf{A} = \begin{bmatrix} a_{11} & \dots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & a_{nn} \end{bmatrix}, \tag{B.7}$$

It is now possible through substitution to express Equation B.5 in terms of the technical coefficients.

Recalling that

$$\mathbf{x} = \mathbf{Z} \cdot \mathbf{i} + \mathbf{f}$$

Equation B.7 can be rearranged using matrix operations to Equation B.8.

$$\mathbf{Z} = \mathbf{A} \cdot \mathbf{x} \tag{B.8}$$

A substitution can be made to yield Equation B.9.

$$\mathbf{x} = \mathbf{A} \cdot \mathbf{x} + \mathbf{f} \tag{B.9}$$

Using matrix operations, it is now possible to introduce the identity matrix in order to rearrange Equation B.9 to Equation B.10 and subsequently to Equation B.11.

$$(\mathbf{I} - \mathbf{A}) \cdot \mathbf{x} = \mathbf{f} \tag{B.10}$$

$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1} \cdot \mathbf{f} \tag{B.11}$$

The Leontief inverse is introduced. This is defined as a constant matrix and can be defined as:

$$\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1} \tag{B.12}$$

$$\mathbf{x} = \mathbf{L} \cdot \mathbf{f} \tag{B.13}$$

## B.3. COST-PUSH DERIVATION

By doing a summation vertically through the FIGARO database it can be found that the total outlays for the each sector for example is Equation B.14.

$$x_j = z_{1j} + \cdots + z_{ij} + \cdots + z_{in} + v_j \tag{B.14}$$

So for sector 1 it would be:

$$x_1 = z_{11} + \cdots + z_{i1} + \cdots + z_{n1} + v_1 \tag{B.15}$$

Now this is normalised, to look at price per unit. In order to see what the increases or decreases are per unit output by sector j.

$$1 = \frac{z_{1j}}{x_j} + \frac{z_{ij}}{x_j} + \frac{z_{in}}{x_j} + \frac{v_j}{x_j} \tag{B.16}$$

Once again the definition of technical coefficient is used.

$$a_{ij} = \frac{z_{ij}}{x_j}$$

Additionally, a new parameter is introduced: the value coefficient. This is defined as the value added per unit output which is mathematically represented by Equation B.17.

$$v_c = \frac{v}{x_j} \tag{B.17}$$

Using the definition of technical coefficient and value coefficient Equation B.16 can be rewritten to Equation B.18.

$$1 = a_{1j} + a_{ij} + a_{in} + v_c \tag{B.18}$$

Using matrix notation this can further be generalised into a matrix equation where $\mathbf{i}'$ is a vector of 1s:

$$\mathbf{i}' = \mathbf{i}' \cdot \mathbf{A} + \mathbf{v_c}' \tag{B.19}$$

This gives prices as 1, which is expected as there are no exogenous price changes in the economy, these are called the base prices. If this is generalised to a price vector, in order to measure variations. Introducing the price vector P yields Equation B.20.

$$\mathbf{p}' = \mathbf{p}' \cdot \mathbf{A} + \mathbf{v_c}' \tag{B.20}$$

Through a similar mathematical process as the previous section:

$$\mathbf{p}' = \mathbf{v_c}' \cdot (\mathbf{I} - \mathbf{A})^{-1} \tag{B.21}$$

Which by the definition of the Leontief inverse yields:

$$\mathbf{p}' = \mathbf{v_c}' \cdot \mathbf{L} \tag{B.22}$$

Transposing yields:

$$\mathbf{p} = \mathbf{L}' \cdot \mathbf{v_c} \tag{B.23}$$

## B.4. TWO SECTOR SENSITIVITY ANALYSIS DERIVATION

With this information, it is possible to formulate two equations to determine the price increase for a sector in terms of $\tau$ and $\mathbf{v_c}$. The equations for the tax on value-added and intermediate sales can be seen in Equation B.26 and Equation B.27, respectively.

$$p_{1\,new} = 0.2 \cdot p_1 + 0.4 \cdot p_2 + v_{c1}\,(1+\tau_1) \tag{B.24}$$

$$p_{1\,new} = 0.3 \cdot (1+\tau_1)\,p_1 + 0.1 \cdot (1+\tau_2)\,p_2 + v_{c1} \tag{B.25}$$

It is assumed that the base prices of sectors 1 and 2 are equal to 1 for simplicity yielding:

$$p_{1\,new} = 0.2 + 0.4 + v_{c1}\,(1+\tau_1) \tag{B.26}$$

$$p_{1\,new} = 0.3 \cdot (1+\tau_1) + 0.1 \cdot (1+\tau_2) + v_{c1} \tag{B.27}$$

# C | Leakage channels

## C.1. The Energy Channel

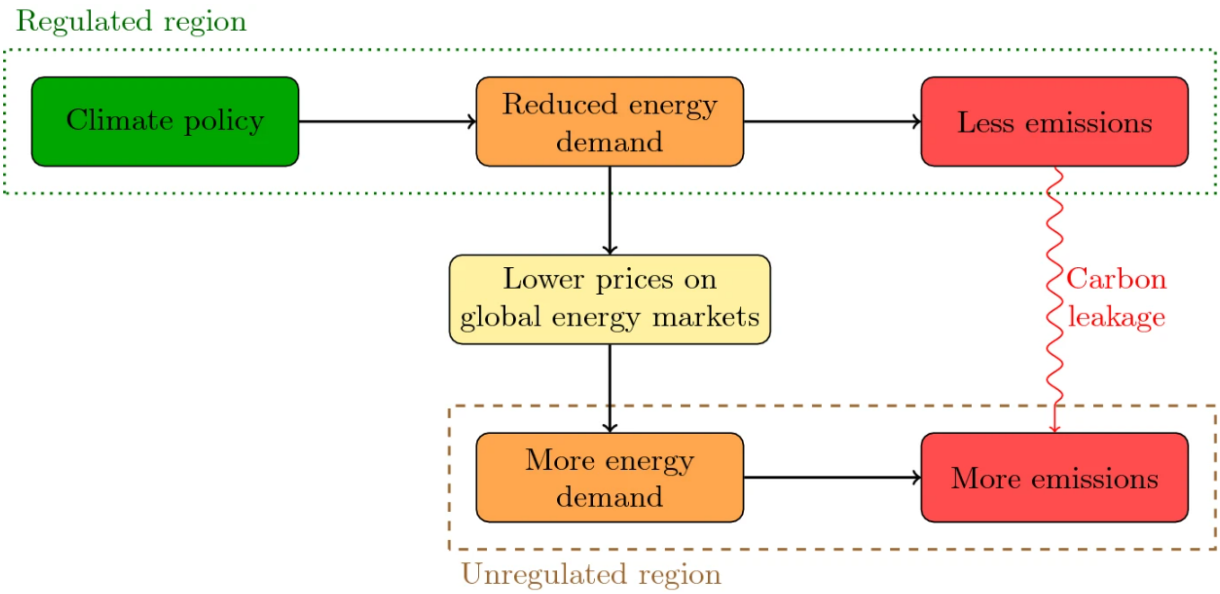
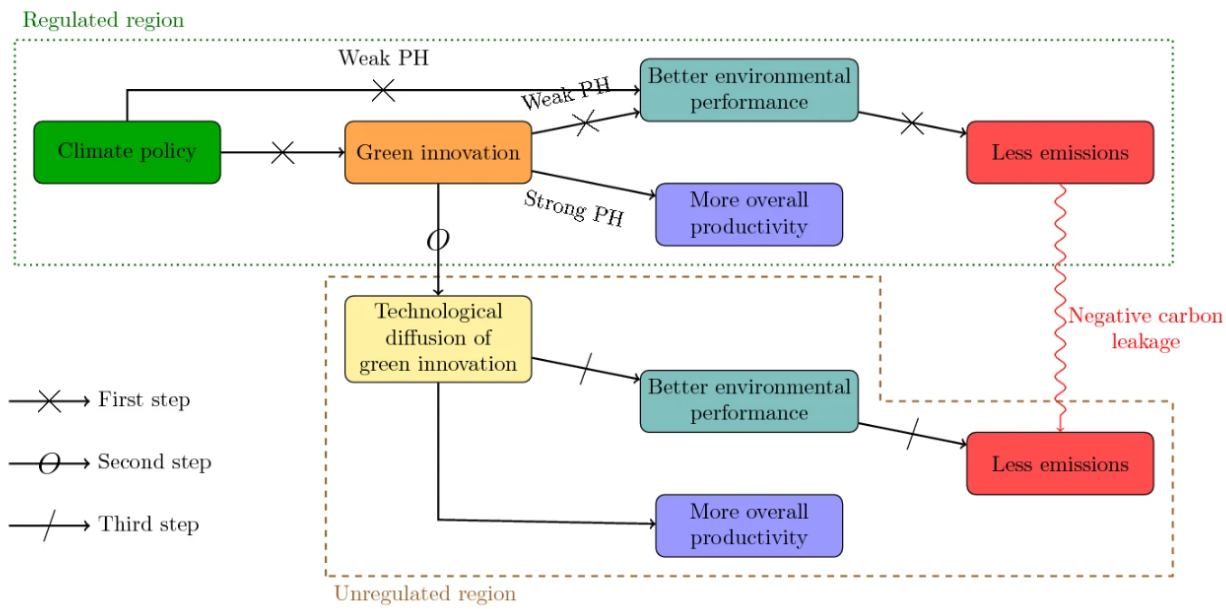



Figure C.1: The energy channel (Cameron and Baudry, 2023)

## C.2. The Innovation Channel




Note: PH = Porter Hypothesis

Figure C.2: The innovation channel (Cameron and Baudry, 2023)