A.N. Jansink

The Global Impact of Carbon Taxation on Carbon Leakage: Analyzing Trends and Policy Effects

Student number: 5147077
First supervisor: Enno Schröder
Chair: Linda Kamp

Abstract

Climate change presents a significant global challenge, prompting governments to adopt a range of mitigation strategies, most notably, carbon pricing schemes. However, such policies are often met with concern over carbon leakage, where emissions reductions in one country are offset by increases elsewhere, potentially undermining the environmental effectiveness of national efforts.

This thesis investigates the relationship between carbon pricing policies and national carbon leakage rates over the period 1995–2018. Drawing on data from the TECO2 dataset and the International and Sectoral Variation in Industrial Energy Prices 1995–2015, and applying the electricity price elasticity methodology introduced by Misch and Wingender (2024), this study calculates annual carbon leakage rates for each country. In doing so, it extends previous research, such as the Misch and Wingender and Sato et al (2019).

A key contribution of this thesis is its novel application of the Carbon Pricing Dashboard, a dataset that remains underutilized in empirical research. This study aims to demonstrate its potential for carbon leakage analysis. Another important contribution is the attempt to extend the methodology developed by Misch and Wingender by applying it not only to CO_2 emissions, as in the original study, but also to broader greenhouse gas emissions. This provides insight into the scope and limitations of their approach when adapted to different types of emissions data. Finally, this thesis contributes to the ongoing policy discussion on carbon pricing by linking yearly carbon leakage rates to country-specific pricing policy variables, such as carbon price levels and policy coverage. In doing so, it investigates whether systematic relationships exist between national carbon pricing strategies and the extent of carbon leakage.

The results indicate that carbon pricing policies explain a meaningful share of the variation in leakage rates across countries, though country-specific fixed effects account for an even larger portion, suggesting that structural or institutional factors may play a more dominant role. Notably, the analysis reveals a negative relationship between carbon pricing and leakage rates, implying that more ambitious pricing policies may actually help reduce leakage. This finding challenges the prevailing narrative in the literature, which often assumes that stricter carbon pricing increases leakage and harms competitiveness. It suggests that policymakers might be able to adopt stronger carbon pricing measures without significant economic drawbacks. Additionally, the study finds no strong evidence that coordinated international carbon pricing efforts lead to greater leakage reductions compared to unilateral national policies, raising questions about the added value of formal international alignment in this context. However, these results should be interpreted with caution. The method used to estimate leakage rates may introduce bias, and further validation is necessary.

That said, the research has some limitations. Most notably, the fixed effects model could not incorporate time fixed effects due to data constraints, raising the risk that some time-related variation may have been wrongly attributed to policy variables. This limitation may partly explain the unexpected direction of some results.

By extending and refining the methodology developed by Misch and Wingender (2024), this thesis offers new empirical insights into the drivers of carbon leakage and contributes to the policy debate on the design and efficacy of national carbon pricing frameworks. In doing so, it also provides a more detailed methodological reflection on the assumptions and limitations inherent in price elasticity-based leakage estimation.

Contents

Table of equations

Table of tables

1. Introduction

1.1. Greenhouse Gas Emissions a Global Problem

Climate change is a critical challenge for society, as it increases the risk and severity of natural disasters and contributes to food and water shortages (Aalst, 2006). These are just a few of the many consequences linked to climate change. The primary driver of climate change is greenhouse gas emissions, which are largely produced by industrial activities, including electricity generation, manufacturing, and transportation (Montzka et al., 2011). These activities burn fossil fuels, releasing carbon dioxide into the atmosphere. Another major source of emissions is deforestation, as trees act as carbon sinks. Cutting down large areas of forest reduces nature's ability to absorb CO_2, further exacerbating climate change (Tubiello et al., 2021).

As greenhouse gas emissions are deeply embedded in modern economies, completely eliminating them overnight would be impossible without causing severe economic disruptions. However, the consequences of climate change are too severe to continue with unchecked emissions. Recognizing this, national governments have taken steps to limit climate change by implementing policies to reduce emissions (United Nations, 2024). In addition to domestic efforts, countries have also made international commitments to limit greenhouse gas emissions by cooperating through global agreements (United Nations, 2024).

Global cooperation is crucial because climate change does not respect national borders. If only a few countries implement emissions reduction policies while others continue emitting at high levels, those making efforts to reduce emissions will still suffer from the global impacts of climate change (Wunder, 2008). This has led to international agreements aimed at coordinating climate action. The first major treaty to address greenhouse gas emissions was the Kyoto Protocol, which aimed to reduce emissions to 5% below 1990 levels by 2012 (United Nations, 1998). Since then, numerous conferences, accords, and agreements have followed (Bodansky, 2001). One of the most significant is the Paris Agreement, in which countries committed to limiting global temperature rise to below 2°C (Paris Agreement, 2015). To achieve this, governments pledged to peak their greenhouse gas emissions as soon as possible and begin reducing them thereafter (Paris Agreement, 2015).

To meet these climate commitments, national governments have implemented various policies to regulate greenhouse gas emissions. The European Union (EU), for example, established the Emission Trading System (ETS), passed by the European Parliament and the European Council (European Parliament and Council, 2024). The ETS places a cap on total emissions, which is then divided into allowances, measured in tons of CO_2 equivalent. These allowances are primarily auctioned off, with some free allowances allocated to certain industries (Verbruggen et al., 2019). Companies can trade these allowances in a regulated marketplace, and those exceeding their limits face substantial fines.

Other governments have opted for carbon taxes instead (World Bank Group, 2024). A carbon tax imposes a levy on emissions based on tons of CO_2 equivalent produced (Narasimhan et al., 2017). The rate of taxation varies by country, much like traditional taxes. However, carbon taxes and ETS mechanisms are not mutually exclusive, some countries implement both systems simultaneously (World Bank Group, 2024).

Reducing emissions is not straightforward. Consider the Netherlands, where there is broad agreement on the need for climate action, yet specific policies often face resistance. For example, when the government lowered speed limits on highways to reduce emissions, it triggered public complaints from commuters (Plicht, 2019). Similarly, when restrictions were imposed on new construction projects, critics argued that the government should focus on expanding housing supply rather than limiting development (Dutch First Chamber (Eerste Kamer), 2024). Climate policies targeting specific industries have also led to organized protests, such as farmers blocking highways in response to emissions regulations.

These conflicts highlight the tensions between environmental policies and economic interests. While governments aim to reduce emissions, affected industries often resist regulations that increase costs or reduce competitiveness. Many businesses support climate neutrality, particularly with the rise of Environmental, Social, and Governance (ESG) criteria (Matos, 2020), but they often advocate for a more gradual transition to avoid economic disadvantages (Dechezleprêtre & Sato, 2017).

The challenges of climate policy implementation are not only domestic but also international. While many governments have committed to agreements such as the Kyoto Protocol and the Paris Agreement, not all countries participate equally (United Nations, 1998). Some countries move faster than others in their climate transition, while others have even considered withdrawing from key agreements (The White House, 2025).

Furthermore, international climate agreements primarily focus on emission reduction targets and measurement standards, rather than prescribing specific policies. As a result, there are vast differences in national climate policies, including varying carbon tax rates, sectoral exemptions, and regulatory structures (United Nations, 1998).

The reasons behind these differences in policy approaches vary. Some countries protect key industries to safeguard economic stability, while others implement laxer regulations to attract businesses seeking lower compliance costs (Jakob, 2021). Developing nations may prioritize economic growth over stringent carbon policies, fearing that strict regulations could hinder development (Pauw et al., 2019).

These regional differences in carbon policies lead to a phenomenon known as carbon leakage. Carbon leakage occurs when emissions reductions in one country lead to an increase in emissions elsewhere, often because industries relocate to regions with weaker environmental regulations.

This thesis will analyze carbon leakage in greater depth in Chapter 2.1, where it will be formally defined. The working definition used in this study is : *“The increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries.”* (Metz & Davidson, 2007).

1.2. Why is Carbon Leakage Important?

Carbon leakage plays a crucial role in the practical realization of climate goals. To illustrate its importance, consider a scenario where carbon leakage is 100%. In this case, if a government successfully reduced all domestic carbon emissions to zero, but those emissions were entirely relocated to another country, global greenhouse gas emissions would remain unchanged. The emissions would have simply shifted to a different location rather than being reduced.

This occurs due to the high level of global economic interconnectivity. For example, if a country eliminates its electricity production to reduce emissions but imports electricity from a neighboring country, the neighboring country might increase its own electricity production to meet demand. If this additional electricity generation produces the same amount of emissions as the original country had reduced, the net effect on global emissions would be zero. This dynamic applies to many industries, where emissions reduced in one country may be offset elsewhere due to shifts in trade and production patterns.

Because emissions and global trade are deeply intertwined, governments and international organizations seek to track emissions and implement policies to prevent leakage. One of the most recent and ambitious efforts to combat carbon leakage is the Carbon Border Adjustment Mechanism (CBAM) proposed by the European Union (EU). CBAM aims to ensure that imported goods face the same carbon pricing, whether through the EU Emissions Trading System (ETS) or carbon taxes, as goods produced within the EU. By accounting for the carbon footprint of imports, CBAM seeks to level the playing field and discourage offshoring emissions-intensive production to countries with weaker climate policies.

However, CBAM remains controversial. Critics argue that it may be difficult to implement due to its complexity, requiring accurate carbon footprint calculations for imported goods. At the same time, some research suggests that carbon leakage is relatively low (Zachmann & McWilliams, 2020), raising questions about whether CBAM is necessary.

On the other hand, supporters of CBAM argue that measured leakage levels appear low only because many regulations exclude high-emission sectors (Grubb et al., 2022). Even if overall leakage rates seem limited, some estimates suggest that leaked emissions still account for up to 25% of total emission reductions (Branger & Quirion, 2014). This suggests that while leakage may not eliminate the benefits of carbon pricing entirely, it could significantly weaken its effectiveness.

To determine the necessity and effectiveness of policies like CBAM, it is essential to analyze global carbon emissions, carbon taxes, and carbon leakage trends. Most existing research on carbon leakage has been conducted at the national or company level, but a broader international analysis of how global policy differences affect leakage rates has not been thoroughly explored. This thesis seeks to answer the central question: *How do global differences in carbon tax policies affect a country's carbon leakage rate*?

To address this, the following sub-questions will be examined:

1. How do you accurately estimate carbon leakage rates?
2. What are the yearly carbon leakage rates of countries?
3. What are the common aspects of countries with high carbon leakage rates?

This thesis will focus on national- and sector-level data, as these sources are the most widely available and standardized. Subnational variations in carbon pricing, such as state- or municipal-level policies, will not be considered.

For example, in Japan, the Tokyo metropolitan government introduced carbon pricing policies earlier than the national government (World Bank Group). However, since this study focuses on national-level policies, Tokyo's pricing will not be separately accounted for. This means that the effective national carbon tax rate may be slightly higher than officially reported, as local initiatives are typically implemented in addition to national policies rather than replacing them. Another is the time scale that was examined namely the period from the year 1995 to 2018.

By analyzing the global landscape of carbon pricing and leakage, this thesis aims to provide new insights into the effectiveness of climate policies and assess whether global coordination is necessary to prevent unintended emissions shifts.

2. Literature Review

2.1 What Is Carbon Leakage

While a uniform definition of carbon leakage is not available, different regions focus on various aspects of carbon leakage (Marcu et al., 2013). Most definitions characterize carbon leakage as the relocation of carbon-intensive production from one region to another following specific events. The Intergovernmental Panel on Climate Change defines carbon leakage as "*the increase in CO_2 emissions outside the countries taking domestic mitigation action divided by the reduction in the emissions of these countries*" (Metz & Davidson, 2007).

-In literature multiple types of carbon leakages are classified. These are meant to give clarity and discuss different nuances of that type of carbon leakage. One of they way people use to discusses carbon leakages are direct and indirect carbon leakage.

-The classical way people think about leakage is direct leakage. This type of leakage is the relocations of parts of the production process to other countries (L'Heudé et al., 2021). This will be done to other countries and regions that are not subject or subject to a lesser carbon tax or move to other sectors that are not subject to the tax (Filippo et al., 2019). This type of leakage is also called leakage through the output channel and is defined as reacting to compliance cost by moving production to another place in the short run (Antoci et al., 2021). If this shift does not happen immediately, companies may instead invest in regions with lower emissions costs rather than in their current region if the expected returns elsewhere are higher, ultimately leading to the same effect over time. This can be called leakage though the invest channel (Antoci et al., 2021). These serve as examples of direct carbon leakage (Zachmann & McWilliams, 2020).

Another type of carbon leakage, known as indirect leakage, is influenced by supply and demand dynamics. Increasing resource consumption efficiency in certain areas reduces the demand for that resource. This, in turn, likely lowers its price, which may encourage countries with less stringent carbon reduction policies to increase their consumption due to the lower cost. As a result, the emissions savings achieved by the policy may be partially offset (Zachmann & McWilliams, 2020). This is also sometimes called leakage through the energy market (Antoci et al., 2021).This type of carbon leakage does not need any direct action from companies or producers of the place subject to the policy, but is a market response through supply and demand (L'Heudé et al., 2021).

-When measuring carbon leakage, also as distinction is made between two types: weak carbon leakage (also known as demand-driven leakage) and strong carbon leakage (also known as policy-induced leakage) (Peters, 2010). Strong carbon leakage is carbon leakage that can directly be attributed to a carbon policy (Davis & Caldeira, 2010). Weak carbon leakage is instead just the overall changes in carbon emissions instead of looking to a specific policy (Peters et al., 2011).

Carbon leakage is typically expressed as a percentage or a dimensionless factor, as it is calculated by dividing changes in CO_2 emissions outside a region by changes in emissions within that region. This ratio inherently lacks a unit. A common formula for calculating carbon leakage is shown in Equation 1 (Michalek & Schwarze, 2015), where $\Delta_P\ E^A$ represents the difference in carbon emissions after a policy implementation in the country that implemented the policy, and $\Delta_P E^B$ represents emissions changes in other regions. The negative sign accounts for the fact that an increase in emissions abroad E^B in response to a reduction at home, E^A, indicates leakage, meaning the policy caused emissions to shift rather than decrease globally.

Equation 1: A mathematical definition of leakage

$$Carbon\ Leakage = -\frac{\Delta_P E^B}{\Delta_P E^A}$$

While it might be expected that carbon leakage rates fall between 0% and 100%, they can, in some cases, exceed 100% or even be negative (Doymea & Dray, 2019). When carbon leakage is negative it implies that the carbon policy took away more emissions than the affected reach was. While carbon leakage rate above 100% means that the targeted reduction leads to an increase in total carbon dioxide emissions.

Negative carbon leakage can occur due to several factors, one of the most notable being technological spillovers (Fullerton et al., 2014) . For instance, carbon reduction policies can drive innovation in industries, resulting in the development of technologies that reduce emissions (Fullerton et al., 2014). These innovations can subsequently diffuse to other regions or sectors, enabling those areas to also lower their emissions. This indirect benefit can offset or surpass the initial emissions reductions in the policy-implementing region, leading to a net global emissions decrease.

Another way that carbon leakage could be negative is by endogeneity of carbon policy (Copeland & Taylor, 2005). As a response to another country taking climate action and producing it, other countries might also take measures reducing the amount of carbon emissions and in turn could result in negative carbon leakage (Copeland & Taylor, 2005).

Also carbon leakage be higher than 100% (Babiker, 2005). This also can happen through multiple reasons (Babiker, 2005). One of the most straight forward ways are cases 100% of the reduction that happens through a reduction of production. The whole chain moves somewhere else to compensate, but that region has less stringent environmental requirements and produces their additional emissions than they did in the original country. Or to another country with exactly the same standards as the first country had but now also produce additional transportation to get the product to the first country (Babiker, 2005).

Because of all these complexities in the supply chain it is difficult to measure how much carbon emissions countries produce as the amount of carbon emissions produced is not equal to the amount of carbon a country consumes. Because of that measuring the emissions of a single country alone is not good enough to combat climate change (Peters et al., 2009). As countries can consume more carbon than they use. If a country has zero carbon emissions, but imports products that used it still in practice has some emissions (Peters & Hertwich, 2008; Sakata et al., 2024).

2.2 How to Estimate Carbon Emissions

Since national accounting of carbon emissions is not a reliable way to measure a country's actual carbon footprint, alternative methods are needed to better understand emissions levels, detect carbon leakage, and assess its magnitude. One approach to obtaining a more accurate picture is through Inter-Country Input-Output (ICIO) tables (Wiebe & Yamano, 2016). Combining ICIO tables with other sources of carbon emissions sources to estimate a trade flow carbon emission (Wiebe & Yamano, 2016).

Production-based accounting for greenhouse gas emissions calculates emissions based on the fossil fuels consumed by a country’s industries and households. However, this method has several limitations. First, emissions generated during international transportation are not attributed to any specific country, as they occur outside national borders (Franzen & Mader, 2019). Additionally, different types of carbon leakage are difficult to detect using this method (Franzen & Mader, 2019). This approach closely resembles the national accounting framework discussed earlier.

To address these shortcomings, consumption-based accounting provides an alternative approach (Franzen & Mader, 2019). This method starts with a country's total emissions but adjusts for trade by subtracting emissions embedded in exported goods and adding emissions associated with imported goods. This leads to consumption-based emissions.

These consumption-based emissions can be used to calculate the weak carbon leakage, as they measure how much carbon is consumed within a territory. If the number of consumption-based emissions is increasing while the amount of territory-based emissions are constant means that the amount of weak carbon leakage is increasing. As this is the overall leakage and not the ones that are attributable to a specific policy (Peters G. P., 2010).

However, consumption-based accounting is not without its challenges. It relies on more assumptions than the production-based approach, making calculations more complex. Additionally, while the difference between production- and consumption-based emissions can be significant for smaller economies, the effect tends to be relatively small for large emitters. Nonetheless, since this thesis focuses on carbon leakage, the consumption-based approach will be used (Franzen & Mader, 2019).

In cases of carbon leakage, consumption-based emissions are expected to decrease less, in relative terms, than production-based emissions. The first widely used dataset for this purpose, TECO2, developed by Wiebe and Yamano, primarily relied on fuel combustion data. The OECD later published an updated version, incorporating distinctions between territorial and residential energy use to improve accuracy (Yamano & Guilhoto, 2020). The most recent dataset, the Greenhouse Gas Footprint Indicators, further expands on this by accounting for non-fuel-based CO_2 emissions (OECD, n.d.). Other datasets using similar methodologies exist, such as Eurostat’s ICIO-based emissions dataset (Eurostat, 2024).

2.3 How to Estimate Carbon Leakage

As discussed in the previous section, a consumption-based approach to measuring carbon leakage is crucial because it allows for a clearer assessment of whether countries offset their domestic emissions reductions by increasing imports. However, measuring carbon leakage is a complex task, as multiple factors can influence changes in consumption-based emissions beyond just leakage. To address this challenge, various methodologies have been developed to estimate carbon leakage. This section will examine these methodologies.

Understanding these different approaches is important because they rely on varying methodologies and parameters, leading to different results. A meta-study has shown that carbon leakage estimates can vary significantly depending on the chosen scenario and methodology. Some studies report negative leakage rates as low as -15%, while others find rates as high as 130% (Xie & Rousseau, 2024). These variations highlight the importance of carefully considering the methodology and context when interpreting carbon leakage estimates.

2.3.1 Computable General Equilibrium Models

Computable General Equilibrium (CGE) models are among the most commonly used models for studying strong carbon leakage (Michalek & Schwarze, 2015). These models estimate the extent of carbon leakage by first constructing a baseline scenario in which no policy is introduced, followed by scenarios where the policy is implemented.

CGE models rely on two key assumptions: the elasticity of fossil fuel supply and the substitutability of products from different origins (Michalek & Schwarze, 2015). Other factors may also be considered depending on the specific model and study (Michalek & Schwarze, 2015). The underlying assumptions are crucial for the model's functionality and can make comparing results across studies challenging. This is evident in a literature review of CGE models, which found that carbon leakage rates typically range between 5% and 30% (Yu et al., 2021).

Several meta-analyses covering different time periods have shown that, on average, CGE models produce higher carbon leakage estimates than other methodologies. For example, a study reviewing 25 papers published between 2004 and 2012 found that CGE models reported leakage rates that were, on average, 9.1% higher than those derived from other methods (Branger & Quirion, 2014). A more recent meta-analysis covering 39 papers published between 2004 and 2022 found an even greater discrepancy, with CGE models consistently yielding higher leakage rates compared to other approaches (Xie & Rousseau, 2024).

2.3.2 Partial Equilibrium Models

Another method commonly used in carbon leakage studies is partial equilibrium models. Like the computable general equilibrium (CGE) models discussed in the previous section, these models focus on market dynamics. However, the key difference is that partial equilibrium models typically analyze a single market, whereas CGE models incorporate multiple markets along with their feedback mechanisms. While this is generally the case, some exceptions can be found in the literature (Paarlberg et al., 2008). How a partial equilibrium model works is that they take a single industry or sector and model the output of emissions pattern. (Ward et al., 2015)

As partial equilibrium models mostly focus on single industries that are heavily vulnerable to carbon emissions policies, they often find different results than the general equilibrium models. Carbon leakage rates can often be found around the 100% (Felbermayr & Peterson, 2020). Another aspect of partial equilibrium models is that they have a build in assumption of positive leakage (Karp, 2010)

2.3.3 Other Methods

While carbon leakage is primarily estimated using the equilibrium models discussed earlier, other methodologies have also been developed. These approaches vary in scope and methodology, ranging from forward-looking projections to backward-looking empirical analyses.

One alternative approach involves the energy–environment–economy model of Europe. This model estimates carbon leakage by comparing scenarios with and without environmental regulations. By simulating differences in CO_2 emissions between these cases, researchers can quantify the extent of carbon leakage (Barker et al., 2007). (This section can be expanded by including specific results and limitations of the study.)

Another method, used by Dechezleprêtre et al. (2022), examines how firms respond to carbon pricing schemes, such as the European Emissions Trading System (ETS). This study compares multinational corporations and applies regression analysis to determine whether their emissions in

Europe changed at a different rate than expected. The researchers found no statistically significant evidence of carbon leakage.

A novel approach proposed by Misch & Wingender (2024) explores how fluctuations in energy prices can be used to estimate changes in domestic carbon production. Their method integrates an accounting framework that enables the assessment of unilateral policy changes. While this model could potentially be applied to compare carbon leakage with national emissions data, it has not yet been used for that purpose, likely due to the study's recent publication. However, this approach presents an opportunity for future research to analyze whether carbon regulations significantly affect leakage rates.

2.4 How Do Policies Influence Carbon Leakage

The reason why leakage occurs is because countries tackling the problem of carbon emissions are not able to tackle the whole problem. Measures on an individual scale are not large enough to tackle this problem. Still carbon policy do have aspects of game theory that also influences collaboration on this problem. So does some research show that the most likely scenario is a group that does take climate action and another group that free rides on the benefits (Carraro, 1998). This is because for each country it is better to pollute more than is optimal for society as a whole (Wood, 2010).

As a study shows is that the amount of carbon leakage becomes lower if the amount of countries participating in the group of carbon taxes becomes lower (Henderson & Verma, 2021). This leads it also to a guiding question throughout this research was inspired by Dechezleprêtre et al. (2022): "*An important question for future research is to understand how large these differences can be before carbon leakage starts becoming an issue (and in which sectors), and how climate policies should be adjusted as other countries' regulations evolve*."

While their study did not find evidence of carbon leakage, it highlights an important aspect: leakage is not solely dependent on a country's own policies but also on the regulatory environment in other countries.

Although some literature examines carbon pricing, much of it does not explicitly address carbon leakage. For instance, one study focused on the effects of carbon emissions reduction, where leakage was considered but classified as a reduction in the country's emissions rather than as a shift in emissions abroad (Le & Azhgaliyeva, 2023). Another study on carbon pricing examined its adoption rather than its effects on leakage (Steinebach et al., 2020). Additionally, some researchers argue that more ex-post analyses on carbon pricing are necessary (Green, 2021). While carbon pricing is widely used as a policy instrument, there remains a significant gap in research on its relationship with carbon leakage.

A sector-specific study estimated that when a greenhouse gas emissions tax is applied to food products, carbon leakage could reach 43% and, in the worst cases, 70% (Zech & Schneider, 2019). A proposed solution to mitigate this effect is expanding global coverage of climate policies, though the study does not quantify how much this would reduce leakage.

While this may be an extreme example, several studies have found no significant evidence of carbon leakage caused by climate policies (Barker et al., 2007; Dechezleprêtre et al., 2022; Grubb et al., 2022). The common explanation across these studies is that, at present, the cost of relocating production outweighs the cost of paying carbon taxes. However, this balance could shift if carbon taxes increase, making it crucial to monitor whether rising carbon costs will eventually make relocation a more attractive option, leading to higher leakage rates.

Emission taxes are not the only policy tool to combat carbon emissions, carbon border adjustment mechanisms (CBAMs) are also designed to prevent carbon leakage. These mechanisms ensure that imported goods account for their embedded carbon emissions in their pricing (European Commission, 2024). This is a policy in response to the fears that direct carbon leakage is occurring from carbon pricing mechanism. (Zhong & Pei, 2023) Some studies suggest that CBAMs could reduce carbon leakage by approximately 4% (Yu et al., 2021). Other research suggest that CBAM is not only good as measure to reduce carbon leakage as it also supports the local industries that get hurt by carbon pricing (Ambec et al., 2024).However, ongoing debates persist regarding their effectiveness, legality, and fairness. Critics argue that CBAMs may not be fully compliant with world trade law (Gehring, 2023) and could disproportionately target developing countries (Zhong & Pei, 2023).

Other research modeling carbon leakage under the Paris Agreement has highlighted significant differences in leakage rates depending on whether countries act cooperatively or unilaterally (King & van den Bergh, 2021). The problem is exacerbated in scenarios where major emitters, such as the United States, withdraw from international agreements. These findings reinforce the idea that international cooperation plays a crucial role in mitigating carbon leakage.

Further evidence of this effect can be seen in the case of Denmark, a country with stricter climate policies than many other EU nations. Research has shown that Denmark experiences a substantially higher carbon leakage rate due to its more stringent regulations compared to its neighbors (Beck et al., 2023). This suggests that even when countries implement climate policies, differences in regulatory stringency can still drive leakage effects.

As demonstrated by the literature, the impact of unilateral policies is not only determined by domestic measures but also by the regulatory actions of other countries. While it seems logical that greater international cooperation would help mitigate leakage, the exact magnitude of this effect remains unclear. Further research is needed to assess how global trends in environmental policy, particularly emissions taxes, impact carbon leakage for individual countries. Some studies have already noted the lack of consideration for global effects in carbon leakage research (Beck et al., 2023). Additionally, the specific impact of varying carbon tax levels on leakage remains an underexplored area in the literature.

3. Methodology

Since no comprehensive database provides direct estimates of a country's carbon leakage, it is essential to first outline the methodology used to estimate these rates. This will be followed by an explanation of how key datasets are extended to support the analysis. Finally, the section will detail the regression analysis used to examine the relationship between carbon leakage and carbon policy. Given the frequent references to Misch & Wingender (2024) and Sato et al. (2019) throughout this section, shorthand notation will be used: M&W for Misch & Wingender (2024) and Sato2019 for Sato et al. (2019).

3.1. Basics of Misch and Wingender

Using an expanded dataset based on Sato2019, this section examines key aspects of M&W study, which estimated carbon leakage rates based on energy price fluctuations. First, it discusses how the original M&W study was reanalyzed using the TECO2 dataset. Next, the thesis tests whether M&W's methodology also produces significant results when applied to greenhouse gases instead of just carbon dioxide.

This section details the data used in the analysis, the methodology employed by M&W, the differences between their approach and the one adopted in this thesis, and the variations in carbon leakage rates observed between their findings and this study.

3.1.1 How to Estimate Carbon Leakage Rates

The impact of a country's carbon emissions on the world can be measured in two ways: production-based (emissions) and consumption-based accounting (Grubb et al., 2022). These two metrics are related, as shown in Equation 2.

Equation 2: Country Carbon Balance

$$\mathrm{C}_i + \mathrm{X}_{i,RW} = \mathrm{Y}_i + \mathrm{M}_{i,RW}$$

In Equation 2, C_i represents the final embodied carbon of goods used in country i, also referred to as the final carbon demand or consumption-based emissions of country i. This reflects the total amount of carbon dioxide associated with the production of goods and services that are ultimately consumed within the country, regardless of where the emissions occurred. $\mathrm{X}_{i,RW}$ denotes the amount of embodied carbon exported from country i to the rest of the world, while Y_i represents the total carbon emissions produced within country i. Lastly, $\mathrm{M}_{i,RW}$ refers to the amount of embodied carbon gases imported into country i from the rest of the world.

Carbon leakage occurs when the government of country i implements an emissions policy (p_i) to reduce domestic carbon emissions, but part of the domestic reduction is offset by an increase in emissions elsewhere. This is referred to as strong carbon leakage, as it can be directly attributed to a specific policy change. As a result, when country i introduces policy p_i, Equation 2, which defines carbon use, can be reformulated to reflect the effects of this policy, as shown below:

Equation 3: Carbon flows in reaction to a policy for country i

$$\frac{\partial C_i}{\partial p_i}\widehat{p_i} + \frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_i} = \frac{\partial Y_i}{\partial p_i}\widehat{p_i} + \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_i}$$

And

Equation 4: Carbon flows for the rest of the world in reaction to policy p

$$\frac{\partial C_{RW}}{\partial p_i}\widehat{p_\iota} + \frac{\partial X_{RW,i}}{\partial p_i}\widehat{p_\iota} = \frac{\partial Y_{RW}}{\partial p_i}\widehat{p_\iota} + \frac{\partial M_{RW,i}}{\partial p_i}\widehat{p_\iota}$$

Equations 3 and 4 illustrate that when the government of country i implements a unilateral policy change, it impacts not only its own production, consumption, imports, and exports but also generates ripple effects across the rest of the world.

For instance, if country i increases its imports as a result of the policy change, the rest of the world must correspondingly increase its exports to country i. Similarly, any imported goods by country i must be exported from somewhere else in the world. The same principle applies when country i exports goods another country must import them.

Building on this fundamental relationship, Equation 5 is derived.

Equation 5: The equivalence between exports and imports

$$\frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_\iota} = \frac{\partial M_{RW,i}}{\partial p_i}\widehat{p_\iota} \;\; and \;\; \frac{\partial X_{RW,i}}{\partial p_i}\widehat{p_\iota} \; = \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_\iota}$$

Using both equation 4 and equation 5 it is possible to conclude the following:

Equation 6: Carbon framework for world balance

$$\frac{\partial C_{RW}}{\partial p_i}\widehat{p_\iota} + \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_\iota} = \frac{\partial Y_{RW}}{\partial p_i}\widehat{p_\iota} + \frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_\iota}$$

$$\frac{\partial C_{RW}}{\partial p_i}\widehat{p_\iota} + \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_\iota} - \frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_\iota} = \frac{\partial Y_{RW}}{\partial p_i}\widehat{p_\iota}$$

$$\frac{\partial Y_{RW}}{\partial p_i}\widehat{p_\iota} = \frac{\partial C_{RW}}{\partial p_i}\widehat{p_\iota} - \left[\frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_\iota} - \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_\iota}\right]$$

Equation 6 demonstrates that the rest of the world's production accounts for both its own consumption and the changes in country i's imports and exports resulting from the implementation of policy p_i. This equation captures the global interdependence of carbon flows, showing how a policy in one country can influence emissions beyond its borders.

Following this M&W proceed by using the definition of carbon leakage, which states that the reduction in carbon emissions within a country due to a policy is partially or fully offset by an increase in carbon production elsewhere in the world.

Equation 7: Defining carbon leakage

$$L(\widehat{p_\iota}) = -\frac{\partial Y_{RW}/\,\partial p_i}{\partial Y_i/\,\partial p_i} = 1 - \frac{(\partial Y_i \; + \partial Y_{RW})/\partial p_i}{\partial Y_i/\partial p_i} = 1 - \frac{\partial Y_G/\,\partial p_i}{\partial Y_i/\,\partial p_i}$$

Where Y_G represents global production, it is defined as the sum of the production of country i and the production of the rest of the world. This leads to the conclusion that carbon leakage is equal to the negative change in carbon emissions in the rest of the world, relative to the change in emissions within country i.

If the policy-induced effects on production are not zero, this relationship can be further refined into a measurable formula, enabling the empirical estimation of carbon leakage as can be seen in equation 8:

Equation 8: Carbon leakage in response to policy p

$$L(\widehat{p_\iota}) \equiv -\frac{\Delta Y_{RW}}{\Delta Y_i}$$

Thus, M&W arrive at the definition of carbon leakage commonly found in the literature. One of the key challenges in estimating carbon leakage due to policy changes using this formula is that multiple factors influence carbon emissions simultaneously. This makes it difficult to isolate the specific impact of policy changes on leakage. To address this, M&W take an alternative approach: rather than directly relying on carbon policy data, they use elasticity estimates to assess the effects of carbon policies more effectively.

Elasticities measure how one variable changes in response to another. M&W suggest that environmental policies are closely linked to energy prices, meaning that analyzing how carbon flows respond to changes in energy prices could provide an indirect way to estimate leakage. To obtain these elasticity estimates, M&W use a dataset from Sato2019, which contains energy price data by sector and country for each year. The dataset and its application will be discussed in more detail in the next section. To estimate elasticity, the following model is used:

Equation 9: Carbon leakage elasticity for energy prices

$$\ln \mathrm{Q}_{i,s,t} = \beta^{\mathrm{Q}} \ln \mathrm{p}_{i,s,t} + \gamma^{\mathrm{Q}}_{i,s} + \theta^{\mathrm{Q}}_{i,t} + \delta^{\mathrm{Q}}_{s,t} + \epsilon^{\mathrm{Q}}_{i,s,t}$$

In this formula, $\mathrm{Q}_{i,s,t}$ represent four different aspects, depending on the specific regression being conducted:
1. Carbon emissions by production in country i for industry sector *s* in year *t*.
2. Carbon emissions embodied in imports, representing the emissions embodied in goods imported by country from industry sector *s* in the rest of the world in year *t*.
3. Carbon emissions embodied in exports, representing the emissions embodied in goods exported by country i from industry sector *s* to the rest of the world in year *t*.
4. Carbon emissions from consumption in country i within industry sector *s* in year *t*.

The parameter β is the regression coefficient for the log of the price. The price data is sourced from Sato2019, though the exact origin of these prices will be discussed further.

The variables γ, θ, and δ represent fixed effects for sector-year, country-year, and country-sector, respectively.

This formula is an exact replication of the one used in M&W. After the elasticities have been estimated these can be used to estimate the amount of carbon leakage. Using the combination of Equation 6 and Equation 8 the following formula can be derived:

Equation 10: Estimating carbon leakage

$$L(\widehat{p_\iota}) = \frac{\frac{\partial C_{RW}}{\partial p_i}\widehat{p_\iota} - \left[\frac{\partial X_{i,RW}}{\partial p_i}\widehat{p_\iota} - \frac{\partial M_{i,RW}}{\partial p_i}\widehat{p_\iota}\right]}{\widehat{\beta^Y} Y_i}$$

$L(\widehat{p_\iota}) = \frac{\widehat{\beta^X} X_{i,RW} - \widehat{\beta^M} M_{i,RW}}{\widehat{\beta^Y} Y_i}$Here, $\widehat{\beta^X} X_{i,\mathrm{RW}}$,$\widehat{\beta^M} M_{i,\mathrm{RW}}$,$\widehat{\beta^Y} Y_i$, represent the import, export, and production elasticities, respectively. This model uses these elasticities to estimate how much imports, exports, and production in country i are affected by energy price changes. By incorporating these effects, it should be possible to evaluate the extent of carbon leakage occurring in a given country.

This formula relies on several key assumptions. First, the model primarily focuses on short-term responses to changes in energy prices, capturing immediate adjustments rather than long-term structural shifts. This means it focus on the production and trade channels, instead of the slower investment channel. Second, it does not account for how other countries might respond to changes in carbon imports and exports. This limitation means that potential feedback effects or adjustments in global trade patterns are not incorporated, which could affect the accuracy of the carbon leakage estimates. These assumptions are important to consider when interpreting the results and assessing their implications for carbon policy.

3.1.2. Data and Changes

To reanalyse and extend the relevant aspects of M&W two central datasets are needed: the previously discussed Sato2019 dataset and the TECO2 dataset. However, this thesis introduces modifications in data selection and methodology to align with its broader research objectives.

Firstly, while M&W use data spanning from 2005 to 2015, this thesis extends the analysis period to 1995–2018. The rationale for this extension is to examine how various factors influencing carbon leakage evolve over time and under different carbon policy regimes. A longer time frame provides a more comprehensive analysis of trends and allows for a better understanding of changes in the elasticity of price. Additionally, climate policies have evolved significantly over this period, making it important to capture their long-term effects. This study will also cover the same industries as M&W, the full list is available Appendix C, but it focuses mostly on industrial sources and does not focus on other areas such agricultural and services.

A small but important difference is that this research uses the 2021 version of the TECO2 dataset, whereas M&W used the 2019 version. The 2021 version was chosen because it extends the data range, covering 1995 to 2018, compared to the 2005–2015 range of the 2019 version (Yamano & Guilhoto, 2020; OECD, 2024). This broader timeframe makes the extended analysis in this thesis possible.

However, the use of the 2021 edition of the dataset introduces some differences compared to the 2019 version used by M&W. For instance, the 2021 edition covers one additional economy not included in the earlier version (OECD, 2024; Yamano & Guilhoto, 2020). In addition, there are differences in country coverage and energy price data. M&W supplemented the dataset with additional energy price indexes for Russia, China, and India, a step that is not replicated in this thesis. Conversely, this thesis extends the dataset by calculating energy price indexes for selected countries after 2015, which were not included in M&W's original work.

Another difference in between the 2019 version of the TECO2 2019 edition compared to the 2021 editions is the version of underlying ICIO tables that are used. The 2019 version used the ICIO of 2018. While this should not make much of a difference it could lead to different results. For example the 2018 ICIO covers only 36 industries while the 2021 covers 45 industries. But the 2021 variant is backwards compatible (Webb, 2022). This means that all the labels, Ids, meanings and data format are the same between the 2021 version and the 2019 version.

Overall, the difference in underlying should be small but can possibly lead to different results and should be taken into consideration when discussing if differences are found between the original M&W paper and the reanalysis.

3.1.2. Greenhouse Gas Elasticity.

Another part of this thesis applies the previously discussed formulas to greenhouse gas emissions rather than just carbon dioxide emissions. While the formulas themselves remain unchanged, any reference to carbon emissions is interpreted in terms of total greenhouse gas emissions. This section uses data from the OECD’s “Greenhouse Gas Footprints” dataset (OECD, 2024).

3.2. Expanding Sato et al.

M&W use the Sato2019 energy prices as their primary source for sectoral energy prices. However, since this dataset only contains data up to 2015, it is necessary for this thesis to extend it by five years to obtain the required data for analysis.

Sato2019 calculates energy prices using a method called the Fixed-Weight Energy Price Index (FEPI). The FEPI provides average prices paid by sectors based on their fuel consumption patterns. It is designed to capture changes in energy prices while maintaining a constant fuel mix, ensuring that price variations are not influenced by shifts in fuel usage.

The FEPI is calculated as follows:

Equation 11: Calculating Fixed-Weight Energy Price Index

$$\mathrm{FEPI}_{\mathrm{ist}} = \sum_{\mathrm{j}} w_{i,s}^{j} \cdot \log\left(\mathrm{P}_{i,t}^{\mathrm{j}}\right) \quad \text{where} \quad \mathrm{w}_{i,s}^{\mathrm{j}} = \frac{\mathrm{F}_{i,s}^{\mathrm{j}}}{\sum_{\mathrm{j}} F_{i,s}^{j}}$$

In this formula, represents the country, *s* denotes the industrial sector, and *j* signifies the fuel type.

Formula 11 illustrates how Sato2019 calculates the Fixed-Weight Energy Price Index (FEPI). The variable P refers to the price in 2010 USD for the respective fuel type, while *w* represents the weights. These weights are determined by categorizing fuel usage into four groups, oil, gas, coal, and electricity, and multiplying this usage by the logarithm of the price for the reference year. Importantly, fuel weights remain constant over time, ensuring that the index isolates energy price fluctuations rather than changes in the fuel mix.

Sato2019 provides several reasons for applying a log transformation to prices. One of the reasons is that this transformation aligns with the best practices for index construction, as outlined in an International Monetary Fund (IMF) report (International Monetary Fund, 2009). This transformation enhances consistency with established methodologies, making the results more accessible to researchers accustomed to standard index construction practices.

Extending the FEPI calculation to 2020 presents a challenge because the exact fuel weights used by Sato et al. are not publicly available. To address this, this thesis approximates the weights by using the average fuel usage per country and sector over the additional five years being added. This adjustment may introduce discrepancies in the post-2015 period, as the estimated weights might differ from those originally used by Sato2019. Leading to data constructed after the year 2015 having different weights and in turn increasing the chance on discrepancies.

Equation 12: Deflating the price

$$\mathrm{P}_{\mathrm{constant}}^{\mathrm{USD}} = \frac{\mathrm{P}_{\mathrm{USD}}^{i}}{\mathrm{Deflator}_{i}}$$

Formula 12 adjusts for inflation in country i , ensuring that energy prices are expressed in real terms over time. However, due to data availability constraints, the dataset could only be extended for a subset of OECD countries, specifically those for which sectoral energy price data is publicly accessible for the additional years. As a result, countries without freely available or complete energy price data during the relevant period could not be included in the extended dataset.

As a result, the dataset is biased toward Western countries as more of their data is included in the regression compared to non-western countries, which may influence the findings. This geographic bias could affect the generalizability of the results, particularly for regions with different energy price dynamics or carbon policy frameworks.

3.3. Calculating Carbon Policy Effects

This section will begin by explaining how the effects of different aspects of carbon policy on leakage will be measured and the reasoning behind these choices. Following this, it will detail the data preparation process, including the key decisions and assumptions made in constructing the dataset.

3.3.1. Estimating the Effects of Carbon Policy on Leakage

In Section 3.1, the methodology for estimating carbon leakage was discussed. Using the previously estimated leakage rates per country per year, this section now examines which factors influence carbon leakage.

The literature suggests multiple potential drivers of carbon leakage, including the coverage of carbon pricing measures, carbon price levels, participation in the EU ETS, and global tax coverage. To identify the most relevant factors, the analysis will begin with a correlation assessment, providing a preliminary understanding of the relationships between these variables and carbon leakage.

Following this exploration phase, several Ordinary Least Squares (OLS) regression models are developed to assess the impact of carbon pricing policies on leakage rates. Specifically, two models will include entity effects for countries, controlling for structural differences and non-policy factors (e.g., economic structure, trade policies) that might influence carbon leakage. These models will then be compared to two identical models without entity effects, allowing for an assessment of whether carbon pricing policies are the primary drivers of leakage.

By comparing these four models, the analysis aims to determine which aspects of carbon pricing policy are most influential, quantify their impact, and assess whether these effects persist beyond country-specific differences. This approach provides a comprehensive understanding of how carbon pricing policies influence carbon leakage.

3.3.2. Data Preparation and Choices

This section describes the construction of the panel dataset used for analysis. The resulting dataset is structured by country and year and includes five key variables: leakage rate, percentage of emissions covered by the instrument, carbon price, global emissions coverage, and each country’s share of global coverage.

The primary dataset used in this analysis is the Carbon Tax Dataset (World Bank Group, 2024), which includes various metrics relevant for assessing the relationship between carbon pricing and leakage rates. However, certain assumptions and compromises were necessary during data preparation to ensure feasibility within the scope of this thesis.

One key compromise in this thesis relates to the share of jurisdictional emissions, which indicates the portion of a country’s emissions covered by a given carbon pricing policy. The dataset provides only a single aggregate coverage value per policy, rather than annual coverage data. As a result, the panel dataset treats this share as fixed from the year the policy takes effect onward. This assumption is unlikely to significantly affect the results. While carbon pricing aims to reduce overall emissions, it is unlikely that the composition of emissions would shift dramatically within the time frame considered. Thus, although the effective coverage rate may gradually decline, the impact on the results should be minimal. Moreover, the dataset includes another variable, the country’s share of total global emissions, which does vary over time and helps to capture some of the dynamics that a time-varying coverage measure would reflect.

Regarding carbon pricing instruments, two main challenges arise. First, some policies establish different prices for different fuel types or greenhouse gases. Given the scope of this thesis, analyzing every price variation across all countries is impractical. Instead, the average price for each policy is used as a representative value. Second, in cases where two different instruments overlap, such as when the EU ETS and a national carbon tax cover the same emissions, each case is addressed individually. Additionally, the price of the carbon pricing instrument is included in the dataset expressed as American Dollar per ton of carbon dioxide equivalent under each policy is included as a key variable in the dataset.

Finally, two additional variables are introduced into the dataset. The first captures each country's share of global emissions covered by carbon pricing instruments, while the second reflects the total global emissions currently subject to carbon pricing. The first variable helps identify shifts in a country's own emissions patterns relative to the global context, while the second is used to assess whether global expansion of carbon pricing influences carbon leakage dynamics. Together, these additions provide a more comprehensive foundation for analyzing the relationship between carbon pricing policies and carbon leakage.

3.3.3. Estimating What Drives Carbon Leakage

This marks a departure from the original methodology of M&W. Building on their leakage estimates, this thesis introduces a new analytical component by conducting five regression analyses. These regressions aim to explore potential models for using the estimated leakage rates to gain deeper insight into the relationship between carbon leakage and various carbon pricing policy variables. In doing so, this section seeks to identify how specific features of carbon pricing, such as implementation, coverage, and price levels, may influence leakage rates, offering a structured extension of the M&W framework with a focus on policy relevance.

Equation 13: Regression 1, mean price

$$\begin{aligned} leak = \beta 0 &+ \beta 1\, price\_mean + \beta 2\, implemented + \beta 3\,(EU\_ETS \times EU\_tax) \\ &+ \beta 4\,(Share\_of\_jurisdiction\_emissions\_covered \times implemented) \\ &+ \beta 5\, world\_emmision\_priced + \beta 6\, global\_coverage + \varepsilon \end{aligned}$$

In this regression formula is the intercept. This is the baseline if all the independent variables would be 0. 1 represents the regression coefficient for the mean price of carbon emissions under the given policy, capturing the influence of carbon pricing on leakage. 2 is a simple coefficient that assesses the overall effect of policy implementation on leakage, regardless of specific price levels or coverage. 3 accounts for European countries participating in the EU Emissions Trading System (EU ETS) by incorporating both membership and the price under the EU ETS, helping to determine whether the system influences carbon leakage differently than other policies. This is a separate pricing variable as countries could have higher carbon pricing than the ETS. measures the effectiveness of the carbon policy in influencing carbon leakage within a country. It is multiplied by an indicator variable that denotes whether the policy has been implemented, serving as a check on whether the introduction of the policy has had an impact. 5 measures how much of the country's total emissions are covered by carbon pricing, examining whether broader coverage leads to higher or lower leakage rates. 6 evaluates whether the current share of global emissions covered by carbon pricing affects leakage, investigating the extent to which international climate policy coordination influences leakage dynamics.

Equation 14: Regression 2, Price difference

$$\begin{aligned} leak \; = \; & \beta 0 \; + \; \beta 1 \, price\_mean\_diff \; + \; \beta 2 \, implemented \; + \; \beta 3 \, (EU\_ETS \; \times \; EU\_tax\_diff) \\ & + \; \beta 4 \, (Share\_of\_jurisdiction\_emissions\_covered \; \times \; implemented) \\ & + \; \beta 5 \, world\_emmision\_priced \; + \; \beta 6 \, global\_coverage \; + \; \varepsilon \end{aligned}$$

The second regression model is structurally identical to the first, with one key difference: it uses the year-over-year change in carbon prices rather than absolute price levels. This adjustment is motivated by Misch and Wingender's discussion of short-term effects, as their elasticity framework is particularly suited to capturing immediate responses to policy changes, rather than long-term structural adjustments. By focusing on price fluctuations rather than static price levels, this model tests whether carbon leakage is more responsive to short-term price shocks. If leakage is significantly affected by sudden changes in carbon pricing, it would suggest that volatility—rather than pricing level alone—plays a critical role in shaping leakage dynamics. This approach aligns with the nature of the M&W methodology, which relies on short-run elasticities that reflect market behavior before firms have time to make longer-term adjustments, such as investments in cleaner technology or relocation. Incorporating short-term price changes into the regression model therefore provides a more appropriate test of the short-term leakage patterns that their method is designed to capture.

Equation 15: Regression 3, fixed effects using the mean price

$$\begin{aligned} leak \; = \; & \beta 1 \, price\_mean \; + \; \beta 2 \, implemented \; + \; \beta 3 \, (EU\_ETS \; \times \; EU\_tax) \\ & + \; \beta 4 \, (Share\_of\_jurisdiction\_emissions\_covered \; \times \; implemented) \\ & + \; \beta 5 \, world\_emmision\_priced \; + \; \beta 6 \, global\_coverage \; + \; \gamma \; + \; \varepsilon \end{aligned}$$

As shown in Equation 15, the formula is almost identical to Equation 13, with two key differences. First, 0 has been removed. Since this is a fixed effects regression, an intercept is no longer necessary. Instead, a new gamma variable is introduced, which creates an intercept for each country. This adjustment allows the model to capture country-specific factors that are not explicitly included in the dataset, accounting for structural differences across nations.

For the fourth regression model, the same structure as the third regression will be used. The key difference, as with the second regression compared to the first, is that it will incorporate price differences instead of absolute price levels. This modification helps assess whether carbon leakage is more sensitive to price volatility rather than static carbon pricing levels.

Equation 16: Regression 4, fixed effects using price difference

$$\begin{aligned} leak \; = \; & \beta 1 price\_mean\_diff \; + \; \beta 2 \, implemented \; + \; \beta 3 \, (EU\_ETS \; \times \; EU\_tax\_diff) \\ & + \; \beta 4 \, (Share\_of\_jurisdiction\_emissions\_covered \; \times \; implemented) \\ & + \; \beta 5 \, world\_emmision\_priced \; + \; \beta 6 \, global\_coverage \; + \; \gamma \; + \; \varepsilon \end{aligned}$$

4. Results

This chapter begins by discussing the main findings on the relationship between carbon pricing policies and carbon leakage, starting with an analysis and comparison of the regression results. The discussion will then shift to a review of how the Sato2019 dataset was extended, detailing the adjustments made to expand its coverage. Following this, the elasticity estimates will be examined, comparing them to those in the M&W paper to assess their consistency. Finally, the chapter will conclude with an evaluation of the leakage rates derived from these elasticities, providing insights into the extent of carbon leakage under different policy scenarios.

4.1. The Link Between Carbon Leakage and Policy Effects

This section presents the main findings by first discussing the results of the regression analyses outlined in Section 3.3.3. Following this, a comparison is made to evaluate how well each model explains the observed variance in carbon leakage. Lastly, a brief discussion highlights the commonalities between the two best-performing models, providing insights into which factors contribute most significantly to explaining carbon leakage.

4.1.1. Regression Analysis

In table 1 all the results are outlined giving for each model the coefficient estimates and the P value for that coefficient.

Table 1 Ordinary Least Squares (OLS) regression results on the effects of carbon pricing on carbon leakage Dependent variable: Carbon leakage rate (1995–2018)

Term	Mean Price Model		Price Change Model		Fixed Effects Mean Price Model		Fixed Effect Price Change Model	
	Estimate	**P value**	**Estimate**	**P value**	**Estimate**	**P value**	**Estimate**	**P value**
Intercept	0.447	< 2e-16 ***	0.45	< 2e-16 ***	-	-	-	-
Mean carbon price	-0.002	5.28e-12 ***	-	-	-0.002	0.1567	-	-
Carbon price change	-	-	-0.002	0.0246 *	-	-	-0.001	0.114
Countries' carbon pricing coverage	-1.44	0.5972	3.034	0.2521	4.146	0.3034	6.532	0.247
Implemented carbon pricing	-0.156	< 2e-16 ***	-0.141	< 2e-16 ***	-0.036	0.193	-0.066	0.204
Global carbon emission covered	-0.166	0.0379 *	-0.147	0.0609 .	0.066	0.6349	-0.0432	0.705
Local emission covered	0.391	< 2e-16 ***	0.252	1.11e-14 ***	0.028	0.6965	0.021	0.805
EU ETS price	0.002	5.74e-05 ***	-	-	0	0.0646 .	-	-
EU ETS price change	-	-	0	0.628	-	-	0	0.731

Note: This table presents regression results across four model specifications assessing the relationship between carbon pricing variables and the dependent variable (carbon leakage rate). Columns 1 and 2 show baseline models using mean price and price change, respectively. Columns 3 and 4 incorporate country and year fixed effects. Asterisks denote significance levels: *** p < 0.001; ** p < 0.01; * p < 0.05; . p < 0.1. Estimates represent the effect size, and p-values indicate the significance of the coefficients. Dashes (–) indicate variables not included in that specification. A full description of variables, their meaning and units can be seen in Appendix B.

As shown in Table 1, most of the coefficients in the non-fixed effect models (model mean price and change model) became statistically significant. While the lowest significance achieved in the fixed effect models is 0.0646, followed by 0.114.

To get a feel of the results first each model will be discussed individually and after that the whole of the results be discussed.

The first statistically significant variable, aside from the intercept, is the carbon price. Its negative coefficient indicates that countries with higher carbon prices tend to experience lower carbon leakage rates. While the effect size appears modest, it becomes meaningful over larger price ranges. For example, the maximum carbon price in the dataset is 108 euros, which corresponds to an estimated 0.2 reduction in leakage, according to the model. This suggests a general trend: higher carbon pricing is associated with lower carbon leakage. Countries with stronger carbon pricing mechanisms tend to exhibit lower leakage rates overall. A more detailed discussion of this finding is provided later in this chapter and in the conclusion.

The percentage of world emissions covered by carbon pricing also has a negative relationship with leakage, indicating that countries implementing broader carbon pricing policies experience lower leakage. This suggests that larger economies might face fewer leakage issues than smaller ones. However, this conclusion should be interpreted with caution. The p-value for this variable is relatively high, and its estimated effect on leakage is quite small, with a maximum impact of less than 0.03. This suggests that, according to this model, global emissions coverage may not significantly influence leakage.

The policy implementation variable ("Implemented") has a statistically significant p-value. Since this variable takes values of 0 or 1, the coefficient indicates that countries that have implemented carbon pricing policies experience, on average, around 0.15 less leakage. However, this result should not be interpreted in isolation. It must be considered alongside the interaction effect between "Implemented" and "Share of Jurisdiction Covered", which has a positive coefficient. The "Share of Jurisdiction Covered" variable ranges between 0 and 1, increasing as a larger share of a country's emissions falls under the carbon pricing policy. This partially offsets the negative coefficient of "Implemented". When more than 43% of a country's emissions are covered, the positive effect of coverage outweighs the negative impact of simply implementing a policy, meaning the stringency of the policy plays a crucial role in determining leakage outcomes.

Global coverage also has a statistically significant negative coefficient, indicating that as more of the world's total emissions become subject to carbon pricing, carbon leakage decreases overall. This finding supports the idea that international coordination on carbon pricing can reduce leakage effects.

The final variable, the interaction between the EU ETS and EU carbon tax pricing, measures how carbon leakage is linked to the price of the EU ETS for countries within the EU. Interestingly, this coefficient is positive, which contrasts with the negative coefficient for standard carbon pricing. This finding is somewhat unexpected, as most of the literature suggests that collective carbon pricing measures should have a weaker individual impact compared to national-level policies. However, in this case, EU ETS pricing appears to be associated with increased leakage. While this can be expected, the fact that non EU ETS price increases lower carbon leakage makes this result strange. This contradicts conventional expectations where initiatives like the EU ETS should lead to lower carbon leakage than unilateral carbon pricing and warrants further investigation.

The results of the second regression model, which is identical to the first but replaces absolute price levels with price differences, are presented below. This alternative specification assesses whether leakage is more sensitive to short-term price shocks rather than to long-term carbon price levels:

The discussion of the results in Table 1 will primarily focus on the differences between this regression model and the price mean regression model. The most important distinction lies in the treatment of mean price versus price differences. While both variables have the same negative coefficient, they capture different aspects of carbon pricing's impact on leakage. The first model examines the absolute price level, while this model focuses on how leakage responds to annual price fluctuations.

The fact that the coefficient for price differences remains negative suggests that in years when carbon pricing increased, overall leakage was lower. This supports the notion that countries with carbon pricing tend to experience lower leakage rates. However, it also implies that short-term price increases, not just long-term high prices, may play a role in reducing leakage, possibly by discouraging carbon-intensive production or incentivizing cleaner alternatives.

Another notable difference is that the EU ETS coefficient is now zero and no longer statistically significant. This likely indicates that changes in the EU ETS price are not linked to carbon leakage, suggesting that fluctuations in EU ETS pricing may have limited short-term effects on firm behavior regarding leakage.

Additionally, global coverage has become slightly less significant compared to the first model. This may suggest that while global emissions coverage is generally associated with lower leakage, its effect is less pronounced when accounting for price fluctuations rather than static pricing levels.

The third regression model builds upon the first regression model by incorporating fixed country effects. This means that the model now estimates a separate intercept for each country, allowing for the control of unobserved, country-specific factors that may influence carbon leakage. The inclusion of fixed effects helps isolate the impact of carbon pricing policies by accounting for structural differences between countries, such as economic composition, energy reliance, and trade policies.

When examining the coefficients in Table 1 for the price change model, several key differences emerge compared to the price mean regression model. The most notable change is that most variables have become statistically less significant. The only variable that comes close to statistical significance is the EU ETS interaction with the EU tax, but its coefficient is zero, indicating that it has no meaningful effect on carbon leakage.

Another important observation is that, while price has become less significant in this model, it retains the same coefficient as in the first model. This suggests that carbon price still holds predictive value, but when accounting for each country's individual mean, the variance increases, likely due to higher clustered standard errors. This indicates that while carbon pricing remains an important factor in leakage, its effect becomes less distinct when controlling for country-specific fixed effects.

Now it is time to compare the results of these 4 models with each other, to gain a better understanding of what the models agree on and disagree on.

The first notable finding is that both mean carbon pricing models display a negative coefficient, suggesting that higher carbon pricing is associated with lower carbon leakage. Although the coefficients are relatively small, carbon prices can reach high levels in practice, making the effect meaningful over time. Additionally, the "Implemented" variable also shows a negative coefficient, indicating that countries with a carbon pricing policy in place generally experience less carbon leakage.

These results challenge the conventional view in much of the literature, which typically finds that carbon pricing increases carbon leakage by raising production costs and incentivizing firms to relocate (Grubb et al., 2022). The findings here suggest that leakage through the investment channel may not be occurring, or at least not in response to the carbon pricing levels observed in this dataset. Rather than causing emissions to shift abroad, higher carbon prices appear to be linked with a net reduction in leakage.

Similar patterns emerge in the price change models, which also yield negative coefficients. This implies that short-term increases in carbon prices, which would be expected to trigger faster-acting leakage mechanisms like the production or trade channels, are likewise associated with reduced leakage. Together, these results suggest that both gradual and sudden increases in carbon pricing do not lead to higher carbon leakage, contradicting widespread concerns about competitiveness impacts.

As shown in Table 1, the most significant difference between the coefficients appears in world emissions priced, which shifts from negative to positive. In the first regression model, the results suggest that countries covering a larger share of global emissions in their carbon pricing policies experience lower leakage. However, Fixed Effects Mean Price Model contradicts this, indicating that greater emissions coverage is instead associated with higher leakage. A similar pattern emerges for global coverage, where the sign of the coefficient also reverses between the models.

Additionally, the magnitude of the coefficients for "Implemented" and its interaction with "Share of Jurisdiction Emissions Covered" is lower in Fixed Effects Mean Price Model compared to the first regression. This suggests that the direct effect of implementing a policy, as well as its interaction with coverage, is weaker when accounting for country-specific fixed effects.

To make a meaningful comparison between models, it is also crucial to analyze the R-squared values, as they provide insight into how much of the variance in leakage rates is explained by each model. The four different R-squared measures all quantify explained variance, but each does so in a slightly different way. This multi-faceted approach ensures a comprehensive understanding of the models' explanatory power and helps identify which specifications best capture the determinants of carbon leakage. But before that it is important to discuss what the R2 metrics do.

The full model R^2 and adjusted R^2 are standard metrics used to indicate how much of the variation in the dependent variable is explained by the model. While both account for all included variables, the adjusted R^2 also applies a penalty for adding additional variables, helping to prevent overfitting. The project model R^2 values, on the other hand, show how much of the variance is explained within groups, such as countries in fixed effects models. In models without fixed effects, the project and full model R^2 values are the same, since the model effectively treats the data as one group (Bartels, 2009).

Table 2 A comparison between the R2 of regression models

Metric	Mean Price Model	Price Change Model	Fixed Effects Mean Price Model	Fixed Effect Price Change Model
Full Model R²	0.1642	0.12	0.8679	0.853
Full Model Adjusted R²	0.1601	0.1157	0.8621	0.8465
Projected Model R²	0.1642	0.12	0.2103	0.121
Projected Model Adjusted R²	0.1601	0.1157	0.1756	0.08233

The R-squared values in Table 2 present a clear pattern. The most notable takeaway is that Regression Fixed Effects Mean Price Model consistently achieves the highest R-squared values across all metrics. This strongly suggests that Fixed Effects Mean Price Model is the most effective at capturing the relationship between carbon leakage and carbon emissions policy.

Fixed Effects Mean Price Model performs particularly well because it incorporates fixed effects for each country, allowing it to account for structural differences that influence leakage beyond carbon pricing policies. However, it also achieves the highest R-squared value in the projected model, which does not include fixed effects. This suggests that even when country-specific factors are excluded, the model still explains a significant portion of the variance in leakage rates. That said, the model performs significantly better when fixed effects are included, indicating that a substantial portion of the variance in leakage is driven by country-specific factors beyond just carbon pricing policies.

Another key observation is that Regressions both price mean models consistently outperform their price change counterpart in terms of explanatory power, as reflected by their higher R-squared values. This suggests that absolute price levels are a better predictor of carbon leakage than price differences. While M&W argue that their method is better suited for predicting short-term fluctuations, one would expect that using their approach to construct leakage estimates would make leakage more sensitive to price hikes than to constant price levels. However, the results indicate that carbon leakage is more closely linked to stable pricing levels rather than short-term price shocks.

One particularly interesting aspect is that Fixed Effects Mean Price Model achieves the highest R-squared value in the projected model despite having very few significant p-values, even fewer than Mean Price Model. This discrepancy suggests that while the model explains a large share of the variance, many individual predictors are not statistically significant. A closer inspection of this issue is necessary to better understand which factors contribute to the model's explanatory power and why fixed effects account for such a large portion of the variance.

So, what do these findings reveal about carbon leakage and carbon policy? The results suggest that carbon pricing is not directly associated with an increase in leakage rates. Moreover, both models indicate that simply implementing a carbon pricing policy does not lead to higher carbon leakage. These findings challenge the assumption that carbon pricing inevitably causes firms to relocate emissions-intensive production, suggesting that other factors, such as global policy coordination, economic structure, or trade dynamics, play a more significant role in determining leakage outcomes.

4.2. Five More Years of Industrial Energy Prices.

As part of expanding data availability for carbon leakage analysis, the industrial energy price dataset needed to be extended. To ensure that the newly added data is consistent and reliable, a validation test was conducted by comparing the descriptive statistics of the extended dataset with the original Sato2019 dataset. This comparison allows for an assessment of whether the newly incorporated data aligns with the trends and distributions observed in the original dataset.

By evaluating key statistical measures, such as mean, standard deviation, and range, this test helps determine whether the extended dataset maintains the integrity of the original energy price data, ensuring that any patterns in carbon leakage estimations remain consistent and interpretable.

Table 3 A comparison between the original Sato2019 data, the subset of countries that was extended and extra country data

Metric	Original	Overlapping countries	Extra
Count	12021	5665	1285
Mean	6.2	6.43	6.45
Min	2.43	5.20	4.03
Max	7.65	7.65	8.01
Std	0.56	0.4	0.49

As shown in Table 3, the original dataset contains 12,021 observations for the Fixed-Weight Energy Price Index (FEPI). The number of observations from countries where additional data was found amounts to 5,665 in the original Sato2019 dataset, while the extended dataset introduces an additional 1,285 FEPI data points. This expansion increases the overall dataset size by approximately 10%, and for the subset of countries with additional data, the increase is around 20%.

The mean FEPI values for the additional years are close to the mean of the original countries in Sato2019, suggesting that the newly incorporated data follows a similar trend. The minimum value in the extra years, while lower than the subset of countries from earlier years, remains within the overall range of the original dataset. The standard deviation of the extended data is slightly higher than that of the subset of countries but remains lower than the original dataset's standard deviation, indicating that the variation in energy prices is not excessively altered by the extension. These findings suggest that extending the dataset has been successful, and the additional data can be reliably used for further analysis in this research.

One particularly interesting observation is the maximum FEPI value found in the extended dataset. The maximum value is significantly higher than the maximum observed in Sato2019. While this difference may seem small at first glance, it is important to consider the logarithmic nature of FEPI. A one-unit increase in FEPI translates to a 40% higher actual energy price, meaning the observed maximum represents a substantial increase.

A closer examination of both the original and extended data reveals an additional insight: the highest FEPI values are not occurring in the same industry or country across different datasets. This suggests that the underlying cause of the higher max values is not simply a continuation of past trends but rather potential structural changes in certain industries or regions.

The most plausible explanation for these differences in maximum values lies in shifts in fuel mix composition. Countries undergoing energy transitions, for example, moving away from fossil fuels toward renewable energy, could experience substantial changes in energy price structures. This transition could have contributed to the higher maximum FEPI values in certain regions. However, this effect is likely limited to specific countries that have undergone significant energy transitions during the years included in the extension.

4.2. Estimated Elasticities

As part of this thesis, the Misch and Wingender (M&W) experiment will be reanalyzed. This process begins by estimating the carbon dioxide elasticity for the period 2005 to 2015, ensuring that the analysis remains as comparable as possible to the original Sato2019 dataset. This allows for a direct assessment of whether the original findings hold under the same conditions.

Following this, the analysis will be extended using data from 1995 to 2018, testing whether the estimated elasticities remain consistent over a longer time period. This extension provides insights into whether the relationships identified by M&W are stable over time or if they vary based on different carbon pricing regimes and economic conditions.

4.2.1. Extending M&W

First, a reanalysis of the M&W method will be conducted for the period 2005 to 2015, using the 2021 version of the TECO2 dataset instead of the original 2019 version, alongside the original Sato2019 energy price dataset. This step aims to determine whether similar results can be replicated using the updated data sources.

Table 4 An analysis of elasticises for the period 2005-2015

Dependent Variable	Coefficient	Standard Error	P Value	Observations
Production CO_2	-0.610	0.192	0.005	7,869
Import CO_2	-0.155	0.051	0.006	7,869
Export CO_2	-0.589	0.187	0.005	7,869
Consumption CO_2	-0.188	0.059	0.005	7,869

The results of the reanalyzed dataset are presented in Table 4. One of the most immediate differences is the lower number of observations compared to the original M&W experiment as they had around 8200 observations for each category. This reduction is likely due to the additional FEPI data points that were created by M&W but not included in this reanalysis.

A key finding is that all variables have now a p value that is statistically significant, marking a notable difference from the original M&W paper. In the original study, the import coefficient did not receive a p value that could be described as statistically significant, whereas in this reanalysis, it now has a p-value of 0.006, indicating a stronger relationship between imports and carbon pricing elasticity.

This is not the only difference between the original M&W results and this reanalysis. The import coefficient, which was slightly positive in the original paper, has now become negative. Additionally, all other coefficients have decreased in magnitude while retaining the same sign as in the original study. These findings strongly suggest that M&W's method remains valid even when applied to an updated dataset, as they still achieve significant results.

Having confirmed the methodology and established support for the results, the analysis is extended to cover the period from 1995 to 2018, allowing for an examination of long-term trends in carbon leakage and price elasticity.

Table 5 An analysis of elasticises for the period 1995-2018

Dependent Variable	Coefficient	StdError	pValue	Observations
Production CO_2	-0.354	0.201	0.093	19,251
Import CO_2	-0.074	0.052	0.175	19,251
Export CO_2	-0.347	0.194	0.089	19,251
Consumption CO_2	-0.092	0.060	0.141	19,251

As shown in Table 9, extending the data range results in higher p-values, indicating that the statistical significance of the relationships decreases. However, the p-values remain sufficiently low, suggesting that the connections are still strong enough for further predictive analysis.

Another notable difference is that all the coefficients magnitude has become less than in the original analysis. This implies that, over a longer time span, the effect of electricity prices on carbon imports, exports, production, and consumption is weaker. In other words, while energy prices remain an important factor in carbon leakage, their influence diminishes when observed over an extended period, potentially due to market adjustments, policy changes, or shifts in energy efficiency and fuel mix over time.

4.2.2. Greenhouse Gas Emissions Results

As part of this thesis, the M&W method was also applied to greenhouse gas emissions, following the same procedure outlined in the methodology chapter, with the only change being the use of greenhouse gas emissions instead of carbon dioxide emissions. The full analysis and results are presented in Appendix B. The main finding was that the regression results yielded p-values close to 1, indicating that the method did not produce statistically significant results when applied to greenhouse gas emissions. This suggests that the M&W methodology may not be effective in this broader context.

A likely explanation for this discrepancy lies in the differences between embodied greenhouse gases and embodied carbon emissions. However, the exact cause is difficult to pinpoint. Since the model already controls for multiple fixed effects, including sector-year, country-year, and country-sector effects, it is unlikely that the issue stems from omitted variable bias related to those dimensions.

One plausible explanation is that greenhouse gas emissions are not as strongly correlated with energy prices as carbon emissions are. Carbon emissions are closely tied to the energy sector, particularly through fossil fuel combustion (Paraschiv & Paraschiv, 2020). In contrast, a substantial share of greenhouse gas emissions originates from non-energy sources, especially agricultural activities. These include methane and nitrous oxide emissions, which are less directly influenced by energy prices, thereby weakening the price-emissions relationship that the M&W method relies on (Lynch et al., 2020).

This finding highlights a key limitation in applying carbon-based methodologies to broader greenhouse gas analyses and underscores the need for tailored approaches when studying non-CO_2 emissions.

4.3. Estimating Leakage Rates

Using the previously estimated elasticities, the next step is to calculate carbon leakage rates and subsequently estimate the effects of carbon pricing policies on leakage. The elasticities applied for this analysis are those from Table 9 as these are the coefficients that that cover the data range.

By plugging in the estimated elasticities and combining them with the respective emissions data, an estimation of each country's carbon leakage rate is obtained for each respective year. This allows for an empirical evaluation of how carbon pricing policies influence leakage over time.

Table 6 Descriptive stats of carbon leakage

	Leakage rate
Mean	0.434160
Min	-0.128681
Max	0.689277
25%	0.402892
75%	0.486245

As shown in Table 6, the leakage rates estimated in this thesis are higher than those found in the original Misch & Wingender (M&W) study. They are also on the higher end of what is reported in other literature, being around the findings of (Zech & Schneider, 2019) that also had a mean around 40% and could reach a maximum of 70%. The findings suggest that carbon emissions are being relocated across borders rather than significantly reduced, indicating that carbon leakage may be a larger issue than previously assumed.

There are multiple possible explanations for these higher leakage rates. One possibility is that errors occurred in the elasticity estimation, leading to an overestimation of leakage effects. Another potential reason could be miscalculations in the extended Sato dataset, which might have skewed the averages, affecting the final estimates. Additionally, it is possible that the M&W method is not well-suited for estimating carbon leakage at this scale, as it was originally designed to analyze short-term responses to energy prices rather than broader, long-term leakage trends.

However, alternative explanations suggest that higher leakage rates could reflect real-world effects rather than methodological errors. It is possible that carbon leakage is more significant than previously assumed, or that pollution havens, where industries relocate to regions with weaker environmental regulations, have offset the expected reductions in emissions. Another key consideration is that this analysis is primarily focused on manufacturing industries, which may be particularly prone to leakage compared to other sectors. If leakage is more pronounced in manufacturing, the findings may not fully represent economy-wide leakage patterns but rather highlight sector-specific vulnerabilities to carbon pricing policies.

5. Conclusions

This thesis sets out to examine how global differences in carbon policy influence carbon leakage across countries. The results of the analysis reveal several findings that are both noteworthy and, at times, counterintuitive. The most surprising result is that higher carbon prices and the implementation of carbon pricing policies are associated with lower carbon leakage rates. This challenges the dominant view in the literature, where carbon pricing is often linked to increased leakage via channels such as production relocation or reduced investment (Marcu et al., 2013). Since carbon pricing directly raises the cost of emissions, a positive relationship with leakage was expected. However, these findings align with more recent work suggesting that unilateral carbon pricing does not necessarily lead to higher leakage rates (Naegele & Zaklan, 2019; Dechezleprêtre et al., 2022).

Several explanations could account for this negative association. One possibility is that carbon prices remain below the threshold where relocation becomes economically viable. Because moving production abroad involves significant costs, many firms may find it more practical to remain within countries that implement carbon pricing, especially when prices are moderate (Dechezleprêtre et al., 2022). A second explanation relates to technological innovation and spillover effects. Carbon pricing can incentivize firms to invest in cleaner technologies rather than relocate, especially if innovation is more cost-effective than moving operations (Fullerton et al., 2014). These two factors combined may create a “Goldilocks zone,” where pricing could be high enough to spur innovation but not high enough to trigger relocation.

A methodological explanation could also account for the negative coefficients. This part of the analysis does not include time fixed effects. Because carbon prices tend to rise over time, and many countries are also independently trying to reduce leakage over time, this general trend may be picked up by the carbon price variable, even if the true causal relationship is weaker or neutral.

Interestingly, the price change models also yield negative coefficients. This indicates that in years where carbon prices rose sharply, carbon leakage decreased. This is counterintuitive, as sudden price hikes are typically expected to induce short-term leakage through the trade or output channels (Misch & Wingender, 2024). Moreover, this result is unlikely to stem from innovation, as technological responses generally occur with a lag. This makes the result even more puzzling than the mean price models.

In contrast to these findings, the policy coverage variable, which captures the share of domestic emissions subject to pricing, shows a positive relationship with leakage across all models. This aligns more closely with existing literature: the broader the scope of a pricing policy, the greater the number of affected sectors, increasing the likelihood that emissions-intensive industries will relocate (Marcu et al., 2013). Sectors like cement and metals are particularly vulnerable, so expanding the policy’s coverage likely increases leakage risk.

This raises an important question: What would an ideal carbon pricing policy look like, based on these findings? The results suggest that the most effective policy in terms of minimizing leakage would combine a high carbon price with narrow coverage focused on sectors less prone to relocation.

The results for the EU ETS price variable are also unexpected. In one model, the coefficient is positive, and in the others, it is close to zero. These values are possibly worse than those for generic carbon pricing policies, despite expectations that coordinated regional approaches like the EU ETS would reduce leakage more effectively than unilateral action (Nielsen et al., 2021; Wood, 2010). This challenges the assumption that international collaboration inherently leads to better outcomes in leakage mitigation.

Still, some findings do support the benefits of global coordination. The variable representing global emissions coverage has a negative coefficient in three of the four models, suggesting that broader adoption of carbon pricing globally reduces incentives for relocation (Carraro, 1998; Beck et al., 2023). This creates a somewhat contradictory picture: broader global coverage is beneficial, but EU ETS participation does not seem to offer clear advantages. Further investigation is needed to understand whether this stems from structural features of the EU ETS or other factors within the EU or methodological failures from this study.

Another variable, the country's share of global emissions covered, does not show consistent results. It lacks statistical significance in all models, and its sign varies across regressions. Both positive and negative interpretations are plausible: larger economies may create stronger relocation incentives, or they may be more self-contained and thus less prone to leakage. The literature generally supports the latter explanation (Beck et al., 2023; Misch & Wingender, 2024).

While these regression results provide valuable insights, they should be interpreted in the broader context of the analysis. The fixed effects in the models account for a much larger share of the variation in leakage rates than any of the policy variables. This suggests that country-specific structural factors, rather than carbon pricing policies themselves, are the primary drivers of carbon leakage. Carbon pricing still plays a role, but its impact appears to be secondary to these broader national characteristics.

This thesis adopted the methodology of Misch and Wingender (2024) to estimate leakage rates and tested its reliability by replicating their experiment. The results closely matched the original findings, with statistically significant coefficients. However, when the method was extended to a longer time period, significance decreased, suggesting that the elasticities weaken over time.

A key limitation of the M&W method was also identified: it does not perform effectively when applied to all greenhouse gas emissions. When the Principal Greenhouse Gas Indicator dataset was used instead of carbon dioxide data, the regression yielded p-values close to 1, indicating a lack of statistical significance. The likely explanation is that the method relies on energy prices to estimate leakage, but many non-CO_2 emissions, such as methane and nitrous oxide, are less directly linked to energy consumption (Lynch et al., 2020). Including these emissions introduces noise into the model, weakening the relationship between prices and emissions.

The elasticities derived from the model revealed an average carbon leakage rate of 43% when applied on national carbon emission data from 1995-2018, 25% higher than found in M&W's original paper and higher than the 5–30% range found in other studies (Yu et al., 2021). This suggests that carbon leakage may be more significant than previously estimated, or alternatively, that this methodology may overstate leakage when applied at scale or under certain assumptions.

These findings are both unexpected and counterintuitive. While some aspects are supported by the existing literature, the results tend to fall on the more extreme end of the spectrum. Specifically, the observed carbon leakage rates are higher than average, and contrary to conventional expectations, leakage appears to decrease as carbon pricing increases. This pattern raises questions about the suitability of the method proposed by Misch and Wingender (2024) for evaluating the policy impacts of carbon pricing on leakage.

Despite these limitations, the findings provide useful insights for policymakers. The results suggest that countries can implement carbon pricing policies without significantly increasing leakage. In fact, the association between higher carbon prices and lower leakage rates offers a promising message: ambitious climate action does not necessarily lead to competitiveness loss. Countries with higher prices tend to experience lower leakage, although this may also reflect structural factors rather than a causal relationship.

However, the findings also suggest that coordinated carbon pricing policies, such as the EU ETS, may not be significantly more effective in reducing carbon leakage than unilateral approaches. In fact, the EU ETS appears to be associated with higher leakage coefficients than its unilateral counterparts. This implies that a unilateral increase in carbon pricing by one euro could result in a smaller increase in leakage compared to a similar increase within the EU ETS. Such a result challenges the assumption that multilateral carbon pricing frameworks inherently offer stronger protection against leakage. It raises concerns about the effectiveness of coordinated pricing as a collaborative mechanism and suggests it may even be counterproductive in certain contexts. Alternative forms of international cooperation, such as harmonized regulatory standards, clean energy subsidies, or targeted trade policies, may therefore offer more promising avenues for reducing global emissions while minimizing leakage.

This thesis makes several contributions to the scientific literature. It evaluates and extends the Misch and Wingender (2024) methodology, confirming its effectiveness for CO_2 emissions while identifying its limitations when applied to broader greenhouse gases. It also finds higher-than-average leakage rates, raising questions about how well current policies contain global emissions displacement.

The study also extends the Sato et al. dataset and demonstrates that repeating the methodology is feasible, though the lack of information precise replication is difficult because of unclear choices from them can lead to variation in results.

This study has several limitations in terms of scope that are important to acknowledge. First, key emitting countries such as China, India, and Russia are underrepresented in the dataset, resulting in fewer observations for these nations. This is particularly relevant given the focus on national-scale emissions trends and carbon leakage, as it may limit the generalizability of the findings. Second, the dataset only extends through 2018, meaning that more recent developments in carbon pricing, many of which have been substantial, are not captured. These more recent policy changes may have significantly influenced carbon leakage patterns in ways that this study does not reflect.

In addition to these scope limitations, there are methodological constraints that could help explain the unexpected results. Most notably, the analysis relies exclusively on linear relationships to estimate the effects of carbon pricing on leakage. However, it is plausible that the underlying dynamics are non-linear or involve threshold effects. For example, Dechezleprêtre et al. (2022) suggest that carbon pricing may only lead to leakage once a certain tipping point is reached. If such threshold effects exist, a linear specification would fail to capture them, potentially distorting the interpretation of results. Similar non-linearities may also apply to other variables included in the model.

Another limitation of this study is its exclusive focus on national-level carbon pricing policies, which does not account for subnational initiatives. In some countries, regions or cities have introduced independent carbon pricing mechanisms that differ from national frameworks. For instance, Tokyo implemented its own carbon pricing system prior to the establishment of a nationwide scheme in Japan (World Bank Group, 2024). By aggregating carbon pricing at the national level, this study may overlook such regional differences, potentially leading to an under- or overestimation of the effective carbon price. As a result, the calculated tax rate could deviate slightly from actual economic conditions, introducing distortions into the analysis.

In addition, there is a structural mismatch between the emissions and pricing datasets. The emissions dataset used in this thesis covers only carbon dioxide (CO_2), while the carbon pricing data includes all greenhouse gases (GHGs). Although this discrepancy does not affect the price variable itself, it could introduce inaccuracies in related variables, particularly global emissions coverage. Since most carbon pricing mechanisms primarily target CO_2, a coverage metric based on total GHGs may overstate the extent to which emissions are actually priced. Consequently, some coverage estimates presented in this study may underrepresent the actual share of CO_2 emissions subject to pricing, affecting the interpretation of the policy's effectiveness.

Finally, the validity of this study hinges on the assumption that sectoral energy prices are a major determinant of carbon leakage. Although this assumption is supported by earlier research, the lack of statistical significance in several key coefficients raises doubts about the strength and consistency of this relationship in the current analysis. This calls into question whether energy prices alone can reliably predict leakage outcomes across different sectors and countries. Further research is needed to better understand the causal mechanisms linking energy prices to carbon leakage, which would help to validate and strengthen the robustness of this study's findings.

One key finding of this study is that fixed effects account for a substantial portion of the variance in carbon leakage rates. This suggests that important country-specific factors, potentially including economic structure, energy mix, or institutional quality, remain unobserved. Future research could focus on identifying and quantifying these underlying variables, thereby providing a more nuanced understanding of what truly drives carbon leakage beyond carbon pricing policies alone.

Another promising research avenue involves expanding the methodological framework developed by Misch and Wingender (2024) to cover all greenhouse gases. As the current approach is limited to carbon dioxide emissions, adapting it to include broader GHG categories would allow for a more comprehensive assessment of leakage, especially in sectors where non-CO_2 emissions play a significant role.

Finally, future studies could investigate whether the effectiveness of carbon pricing policies varies at higher price levels. If firms only begin relocating emissions-intensive activities once carbon prices exceed a certain threshold, identifying that tipping point would be critical for designing more effective and leakage-resistant policy instruments. Such insights could support policymakers in calibrating carbon prices to balance environmental ambition with economic competitiveness.

The findings of this study offer strong support for national governments to pursue climate action through carbon pricing. Although carbon leakage remains a concern, the results suggest that countries can implement carbon pricing policies without significantly exacerbating leakage rates. In fact, the observed negative relationship between carbon pricing levels and leakage rates indicates that more ambitious pricing mechanisms may contribute to reducing overall emissions rather than displacing them.

Crucially, the leakage rates estimated in this study remain well below 100%, implying that carbon pricing policies still yield net global emissions reductions. While some emissions may shift across borders, the broader impact of carbon pricing appears to be a decline in total greenhouse gas emissions. This finding strengthens the case for continued policy efforts, affirming that individual countries can meaningfully contribute to global climate goals—even in the absence of full international coordination.

Bibliography

The European Parliament and the Council . (2024, March 1). *Consolidated text: Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (Text with EEA relevance).* From eur-lex.europa.eu: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02003L0087-20240301

Aalst, M. K. (2006). The impacts of climate change on the risk of natural disasters. *Special Issue:Climate change and disasters, 30*(1), 5-18. https://doi.org/10.1111/j.1467-9523.2006.00303.x

Ambec, S., Esposito, F., & Pacelli, A. (2024). The economics of carbon leakage mitigation policies. *Journal of Environmental Economics and Management, 125*, 102973. https://doi.org/10.1016/j.jeem.2024.102973

Antoci, A., Borghesi, S., Iannucci, G., & Sodini, M. (2021). Should I stay or should I go? Carbon leakage and ETS in an evolutionary model. *Energy Economics, 103*, 105561. https://doi.org/10.1016/j.eneco.2021.105561

Babiker, M. H. (2005). Climate change policy, market structure, and carbon leakage. *Journal of International Economics, 65*(2), 421-445. http://dx.doi.org/10.1016/j.jinteco.2004.01.003

Barker, T., Junankar, S., Pollitt, H., & Summerton, P. (2007). Carbon leakage from unilateral Environmental Tax Reforms in Europe, 1995–2005. *Energy Policy, 35*(12), 6281-6292. https://doi.org/10.1016/j.enpol.2007.06.021

Bartels, B. L. (2009). Beyond Fixed versus Random Effects: A Framework for Improving Substantive and Statistical Analysis of Panel, Time-Series Cross-Sectional, and Multilevel Data. *Quantitative Research in Political Science, 9*, 1-43.

Beck, U. R., Kruse-Andersen, P. K., & Stewart, L. B. (2023). Carbon leakage in a small open economy: The importance of international climate policies. *Energy Economics, 117*, 106447. https://doi.org/10.1016/j.eneco.2022.106447

Bodansky, D. (2001). The History of the Global Climate Change. In U. Luterbacher, & D. F. Sprinz, *International Relations and Global Climate* (pp. 23-41). Massachusetts Institute of Technology.

Brange, F., & Quirion, P. (2014). Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies. *Ecological Economics, 99*, 29-39. https://doi.org/10.1016/j.ecolecon.2013.12.010

Carraro, C. (1998). Beyond Kyoto: A Game-Theoretic Perspective. *The Proceedings of the OECD Workshop on "Climate Change and Economic Modelling. Background Analysis for the Kyoto Protocol.* Paris.

Copeland, B. R., & Taylor, M. S. (2005). Free trade and global warming: a trade theory view of the Kyoto protocol. *Journal of Environmental Economics and Management, 49*(2), 205-234. https://doi.org/10.1016/j.jeem.2004.04.006

Davis, S. J., & Caldeira, K. (2010). Consumption-based accounting of CO2 emissions. *Proc Natl Acad Sci U S A., 107*(12), 5687–5692. https://doi.org/10.1073/pnas.0906974107

Dechezleprêtre, A., & Sato, M. (2017). The Impacts of Environmental Regulations on Competitiveness. *Review of Environmental Economics and Policy, 11*(2), 183-206. https://doi.org/10.1093/reep/rex013

Dechezleprêtre, A., Gennaioli, C., Martin, R., Muûls, M., & Stoerk, T. (2022). Searching for carbon leaks in multinational companies. *Journal of Environmental Economics and Management, 112*, 102601. https://doi.org/10.1016/j.jeem.2021.102601

Doymea, K., & Dray, L. (2019). Carbon Leakage in Aviation Policy. *Climate Policy, 19*(10), 1284-1296. https://doi.org/10.1080/14693062.2019.1668745

Dutch First Chamber (Eerste Kamer). (2024, April 23). Minutes of the meeting of 23 April 2024 (2023/2024 no. 30) (Verslag van de vergadering van 23 april 2024 (2023/2024 nr. 30).

European Commission. (2024, October 2024). *Carbon Border Adjustment Mechanism*. From taxation-customs.ec.europa.eu: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

Eurostat. (2024). *FIGARO – Greenhouse gas emission Methodological note.* European Commission.

Felbermayr, G., & Peterson, S. (2020). *Economic assessment of Carbon Leakage and Carbon Border Adjustment.* European Parliament. From https://policycommons.net/artifacts/1337187/economic-assessment-of-carbon-leakage-and-carbon-border-adjustment/1944860/

Franzen, A., & Mader, S. (2019). Consumption-based versus production-based accounting of CO2 emissions: Is there evidence for carbon leakage? *Environmental Science & Policy, 84*, 34-40. https://doi.org/10.1016/j.envsci.2018.02.009

Fullerton, D., Karney, D., & Baylis, K. (2014). Negative leakage. *Journal of the Association of Environmental and Resource Economists, 1*(1/2), 51-73. https://doi.org/10.1086/676449

Gehring, M. (2023). Border Carbon and the CBAM Mechanism's legality in the EU Legal Order. *Legal Studies Research Paper Series, 7*. http://dx.doi.org/10.2139/ssrn.4409236

Green, J. F. (2021). Does carbon pricing reduce emissions? A review of ex-post analyses. *Environmental Research Letters, 16*(4). https://doi.org/10.1088/1748-9326/abdae9

Grubb, M., Jordan, N. D., Hertwich, E., Neuhoff, K., Das, K., Bandyopadhyay, K. R., . . . Oh, H. (2022). Carbon Leakage, Consumption, and Trade. *Annual Review of Environment and Resources, 47*(1), 753-795. https://doi.org/10.1146/annurev-environ-120820-053625

Henderson, B., & Verma, M. (2021). *Global Assessment of the Carbon Leakage Implications of Carbon Taxes on Agricultuaral Emissions.* OECD Food, Agriculture and Fisheries Paper No. 170. OECD.

International Monetary Fund. (2009). *Export and Import Price Index Manual Theory and Practice.* International Monetary Fund.

Jakob, M. (2021). Why carbon leakage matters and what can be done against it. *One Earth, 4*(5), 609-614. https://doi.org/10.1016/j.oneear.2021.04.010

Karp, L. (2010). *Carbon Leakage in General and Partial Equilibrium.* Unpublished manuscript. Department of Agricultural and Resource Economics, University of California, Berkeley.

King, L. C., & van den Bergh, J. C. (2021). Potential carbon leakage under the Paris Agreement. *Climatic Change, 165*(3-4), 52. https://doi.org/10.1007/s10584-021-03082-4

L'Heudé, W., Chailloux, M., & Jardi, X. (2021). *A Carbon Border Adjustment Mechanism for the European Union.* Le ministère de l'Économie, des Finances et de la Relance, (280).

Le, H., & Azhgaliyeva, D. (2023). Carbon pricing and firms' GHG emissions: Firm-level empirical evidence from East Asia. *Journal of Cleaner Production, 429*, 139504. https://doi.org/10.1016/j.jclepro.2023.139504

Lynch, J. M., Cain, M., Frame, D., & Pierrehumbert, R. (2020). Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2-Emitting Sectors. *Front. Sustain. Food Syst, 4*, 518039. https://doi.org/10.3389/fsufs.2020.518039

Marcu, A., Egenhofer, C., Roth, S., & Stoefs, W. (2013, December 6). Carbon Leakage: An overview. *CEPS Special Report No. 79*. Centre for European Policy Studies.

Matos, P. (2020). *ESG and responsible institutional investing around the world: A critical review.* Matos, Pedro, ESG and Responsible Institutional Investing Around the World: A CFA Institute Research Foundation Literature Reviews. https://dx.doi.org/10.2139/ssrn.3668998

Michalek, G., & Schwarze, R. (2015). Carbon leakage: pollution, trade or politics? *Environment, Development and Sustainability, 17*, 1471–1492. https://doi.org/10.1007/s10668-014-9616-8

Misch, F., & Wingender, P. (2024). Revisiting Carbon Leakage. *Energy Economics, 140*, 107786. https://doi.org/10.1016/j.eneco.2024.107786

Montzka, S. A., Dlugokencky, E. J., & Butler, J. H. (2011). Non-CO2 greenhouse gases and climate change. *Nature, 476*, 43-50. https://doi.org/10.1038/nature10322

Naegele, H., & Zaklan, A. (2019). Does the EU ETS cause carbon leakage in European manufacturing? *Journal of Environmental Economics and Management, 93*, 125-147. https://doi.org/10.1016/j.jeem.2018.11.004

Narassimhan, E., Gallagher, K. S., Koester, S., & Alejo, J. R. (2017). *Carbon Pricing in Practice: A Review of the Evidence.* Medford, MA. Climate Policy Lab. From worldbank.org.

Netz, B., Davidson, O. R., Bosch, P. R., Dave, R., & Meyer, L. A. (2007). *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Intergovernmental Panel on Climate Change (IPCC). From https://www.cabidigitallibrary.org/doi/full/10.5555/20083115500

Nielsen, T., Baumert, N., Kander, A., Jiborn, M., & Kulionis, V. (2021). The risk of carbon leakage in global climate agreements. *International Environmental Agreements: Politics, Law and Economics, 21*(1), 147-163. https://doi.org/10.1007/s10784-020-09507-2

OECD. (2024, September 20). *Greenhouse gas footprint indicators*. Retrieved October 1, 2024 from oecd.org: https://data-explorer.oecd.org/vis?tenant=archive&lc=en&df[ds]=DisseminateArchiveDMZ&df[id]=DF_IO_GHG_2021&df[ag]=OECD&df[vs]=1.0&av=true&dq=...&lom=LASTNPERIODS&lo=5&to[TIME_PERIOD]=false

Paraschiv, S., & Paraschiv, L. S. (2020). Trends of carbon dioxide (CO2) emissions from fossil fuels combustion (coal, gas and oil) in the EU member states from 1960 to 2018. *Energy Reports, 6*(3), 237-242. https://doi.org/10.1016/j.egyr.2020.11.116

Pauw, P., Mbeva, K., & Asselt, H. v. (2019, July 30). Subtle differentiation of countries' responsibilities under the Paris Agreement. *Palgrave Communications, 5*(86). https://doi.org/10.1057/s41599-019-0298-6

Peters, G. P. (2010). Policy Update: Managing carbon leakage. *Carbon Management, 1*(1), 35–37. https://doi.org/10.4155/cmt.10.1

Peters, G. P., & Hertwich, E. G. (2008). CO2 Embodied in International Trade with Implications for Global Climate Policy. *Environmental Science & Technology, 42*(5), 1401–1407. https://doi.org/10.1021/es072023k

Peters, G. P., Marland, G., Hertwich, E. G., Saikku, L., Rautiainen, A., & Kauppi, P. E. (2009). Trade, transport, and sinks extend the carbon dioxide responsibility of countries: An editorial essay. *Climatic Change, 97*, 379-388. https://doi.org/10.1007/s10584-009-9606-2

Peters, G. P., Minx, J. C., Weber, C. L., & Edenhofer, O. (2011). Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the National Academy of Sciences, 108*(21), 8903–8908. https://doi.org/10.1073/pnas.1006388108

Plicht, J. v. (2019, September 25). *Advies commissie: Snelheidsverlaging nodig om uitstoot stikstof te beperken*. From nu.nl: https://www.nu.nl/binnenland/5998261/advies-commissie-snelheidsverlaging-nodig-om-uitstoot-stikstof-te-beperken.html#nujij

Sakata, S., Aklilu, A. Z., & Pizarro, R. (2024). Greenhouse Gas Emissions Data: Concepts and Data Availability. *SDD Working Paper, 122*. https://doi.org/10.1787/b3e6c074-en

Steinebach, Y., Fernández-i-Marín, X., & Aschenbrenner, C. (2020). Who Puts a Price on Carbon, Why and How? A Global Empirical Analysis of Carbon Pricing Policies. *Climate Policy, 21*(9), 277-289. https://doi.org/10.1080/14693062.2020.1824890

The White House. (2025, January 20). *Putting America First in International Environmental Agreements*. From whitehouse.gov: https://www.whitehouse.gov/presidential-actions/2025/01/putting-america-first-in-international-environmental-agreements/

Tubiello, F. N., Conchedda, G., Wanner, N., Federici, S., Rossi, S., & Grassi, G. (2021). Carbon emissions and removals from forests: new estimates, 1990–2020. *Earth System Science Data, 13*(4), 1681–1691. https://doi.org/10.5194/essd-13-1681-2021

United Nations. (1998). Kyoto Protocol to the United Nations Framework Convention on Climate Change. From https://unfccc.int/resource/docs/convkp/kpeng.pdf

Verbruggen, A., Laes, E., & Woerdman, E. (2019). Anatomy of Emissions Trading Systems: What is the EU ETS? *Environmental Science & Policy, 98*, 11-19. https://doi.org/10.1016/j.envsci.2019.05.001

Ward, J., Sammon, P., Dundas, G., Peszko, G., & Kennedy, P. (2015). *Carbon Leakage Theory, Evidence and Policy Design.* International Bank for Reconstruction and Development, The World Bank.

Webb, C. (2022, October 12). *Ongoing and future developments of OECD ICIO tables and GVC indicators.* From worldklems.net:

https://www.worldklems.net/conferences/worldklems2022/10_13_22_Dalton/9_00_Webb.pdf

Wiebe, K. S., & Yamano, N. (2016). Estimating CO2 Emissions Embodied in Final Demand and Trade Using the OECD ICIO 2015. *OECD Science, Technology and Industry Working Papers, 5*. https://doi.org/10.1787/5jlrcm216xkl-en

Winning, M., P. J., Ekins, P., Pye, S., Glynn, J., W. J., & McGlade, C. (2024). Nationally Determined Contributions under the Paris Agreement and the costs of delayed action. *Climate Policy, 19*(8), 947–958. https://doi.org/10.1080/14693062.2019.1615858

Wood, P. J. (2010). Climate Change and Game Theory. *Annals of the New York Academy of Sciences, 1219*(1), 153-170. https://doi.org/10.1111/j.1749-6632.2010.05891.x

World Bank Group. (2024, April 1). *State and Trends of Carbon Pricing Dashboard.* Retrieved December 25, 2024 from carbonpricingdashboard.worldbank.org: https://carbonpricingdashboard.worldbank.org/about#download-data

Wunder, S. (2008). How do we deal with leakage? In A. Angelsen, *Moving Ahead with REDD* (Vol. 1, pp. 65-75). Center for International Forestry Research.

Xie, M., & Rousseau, S. (2024). Policy solutions for addressing carbon leakage: Insights from meta-regression analysis. *Journal of Environmental Management, 365*, 121557. https://doi.org/10.1016/j.jenvman.2024.121557

Yamano, N., & Guilhoto, J. (2020). CO2 emissions embodied in international trade and domestic final demand: Methodology and results using the OECD Inter-Country Input-Output Database. *OECD Science, Technology and Industry Working Papers, 2020/11*. https://doi.org/10.1787/8f2963b8-en

Yu, B., Zhao, Q., & Wei, Y. (2021). Review of carbon leakage under regionally differentiated climate policies. *Science of the Total Environment, 782*, 146765. https://doi.org/10.1016/j.scitotenv.2021.146765

Zech, K. M., & Schneider, U. A. (2019). Carbon leakage and limited efficiency of greenhouse gas taxes on food products. *Journal of Cleaner Production, 213*, 99-103. https://doi.org/10.1016/j.jclepro.2018.12.139

Zhong, J., & Pei, J. (2023). Carbon border adjustment mechanism: a systematic literature review of the latest developments. *Climate Policy, 24*(2), 228-242. https://doi.org/10.1080/14693062.2023.2190074

Appendix A Correlation matrix

Correlation Matrix

Variable	Leak	Year	Global Coverage	Share of Jurisdiction Emissions Covered	Price Mean	Price Median	% World Emission Priced	EU Tax	Mean Diff	Median Diff	EU Tax Diff
Leak	1	0.017	0.010	0.085	0.062	0.062	0.143	0.011	0.038	0.038	0.019
Year	0.017	1	0.481	0.050	0.261	0.261	0.128	-0.209	0.047	0.047	-0.085
Global Coverage	0.010	0.481	1	0.577	0.376	0.376	0.218	0.343	0.079	0.079	0.022
Share of Jurisdiction Emissions Covered	0.085	0.050	0.577	1	0.302	0.302	0.233	0.442	0.041	0.041	0.026
Price Mean	0.062	0.261	0.376	0.302	1	1	0.150	0.096	0.270	0.270	0.006
Price Median	0.062	0.261	0.376	0.302	1	1	0.150	0.096	0.270	0.270	0.006
% World Emission Priced	0.143	0.128	0.218	0.233	0.150	0.150	1	0.005	0.055	0.055	0.000
EU Tax	0.011	-0.209	0.343	0.442	0.096	0.096	0.005	1	0.036	0.036	0.530
Mean Diff	0.038	0.047	0.079	0.041	0.270	0.270	0.055	0.036	1	1	0.036
Median Diff	0.038	0.047	0.079	0.041	0.270	0.270	0.055	0.036	1	1	0.036

Appendix B Variable Explanations

Equation Name	Table 1 Name	Description	Units
price_mean_diff	Carbon price change	Annual change in the average carbon price for a country or jurisdiction.	US$/tCO$_2$e
price_mean	Mean carbon price	Average carbon price over the year.	US$/tCO$_2$e
implemented	Implemented carbon pricing	Indicates whether a carbon pricing mechanism is implemented (e.g., 0 or 1).	Dimensionless
EU_ETS	–	Indicator for participation in the EU Emissions Trading System.	Dimensionless
EU_tax_mean	EU ETS price	Average annual carbon price under the EU ETS.	US$/tCO$_2$e
EU_tax_diff	EU ETS price change	Year-over-year change in EU ETS carbon price.	US$/tCO$_2$e
world_emmission_priced	Local emission covered	Proportion of a country's emissions covered by carbon pricing mechanisms, expressed as a share of total global emissions.	Dimensionless
global_coverage	Global carbon emission covered	Share of global greenhouse gas emissions subject to any carbon pricing policy.	Dimensionless
Share_of_jurisdiction_emissions_covered	Countries' carbon pricing coverage	Share of each jurisdiction’s emissions that are covered by carbon pricing.	Dimensionless

Appendix C Greenhouse gas Elasticity

This thesis originally used the principal greenhouse indicator dataset, what measures greenhouse gas emissions instead of carbon dioxide emissions. The reasons why this dataset was not used in the end will be shown below.

Firstly it started by reanalyzing the M&W paper by using the same time frame from 2005 – 2015. This was done to analyze the amount leakage that would have happened when applying the same method on the same time frame but with a different data set.

Table 7 Elasticity 2005-2015

DependentVariable	Coefficient	StdError	pValue	Observations
Production CO_2	-0.246	0.207	0.253	6,345
Import CO_2	0.016	0.056	0.775	6,345
Export CO_2	-0.222	0.196	0.275	6,345
Consumption CO_2	0.003	0.071	0.971	6,345

The first thing in Table 2 is that none of the values in this replication achieve statistical significance. This contrasts with the original findings by Misch and Wingender, where consumption, production, and exports were statistically significant. While imports were not statistically significant in either case, their effect was slightly positive in the original paper but appears slightly negative in this replication. Despite these differences, some patterns remain consistent when transitioning to the new Principal Greenhouse Gas Indicator dataset. Both production and exports show strongly negative coefficients and have the lowest p-values, suggesting they are the most statistically significant variables in this context.

The prevopis data seems to imply that the method does not leed to significant results. To confirm the results a bigger time frameee has been taken to analyse. The confirmation analysis takes a time frame from 1995 to 2020. This was done to se whether the p values improve or worsen.

Table 8 Elasticity 1995-2020

Dependent Variable	Coefficient	StdError	pValue	Observations
Production CO_2E	0.011	0.070	0.882	16,173
Import CO_2E	0.004	0.034	0.912	16,173
Export CO_2E	0.008	0.070	0.909	16,173
Consumption CO_2E	0.002	0.035	0.950	16,173

This results in table 5 show a conlusive that taking the whole time from 1995 to 2020 does not lead to any statsical significance. That is because the value of the observed data is extremely high and the coefficients are small, meaning that they could practically be 0. So, either it is not significant, or it is zero, both options make this unfit. This seems as conclusive proof that the elasticity is not consistent throughout the whole period. This makes greenhouse gas data unusable with energy prices for estimating elastic. This was the reason why this thesis dcided to also use carbon emissions from the TECO2 data set instead of using the greenhouse gases from the principal greenhouse indicator dataset.

Appendix D Data set information

Country comparison M&W and Here

Country	ISO3	Original	Extended
Cyprus	CYP	X	✓ Included
Norway	NOR	✓ Included	✓ Included
Thailand	THA	X	✓ Included
Portugal	PRT	✓ Included	✓ Included
Russia	RUS	✓ Included	✓ Included*
Czech Republic	CZE	✓ Included	✓ Included
Australia	AUS	✓ Included	✓ Included
Spain	ESP	✓ Included	✓ Included
Romania	ROU	X	✓ Included
Japan	JPN	✓ Included	✓ Included
Switzerland	CHE	✓ Included	✓ Included
New Zealand	NZL	✓ Included	✓ Included
Germany	DEU	✓ Included	✓ Included
Estonia	EST	X	✓ Included
Slovenia	SVN	✓ Included	✓ Included
Ireland	IRL	✓ Included	✓ Included
India	IND	✓ Included	✓ Included*
Indonesia	IDN	✓ Included	✓ Included
Austria	AUT	✓ Included	✓ Included
Belgium	BEL	✓ Included	✓ Included
Croatia	HRV	X	✓ Included
Taiwan	TWN	X	✓ Included
Kazakhstan	KAZ	X	✓ Included
Chile	CHL	X	✓ Included
Bulgaria	BGR	✓ Included	✓ Included
Turkey	TUR	✓ Included	✓ Included
Canada	CAN	✓ Included	✓ Included
Hungary	HUN	✓ Included	✓ Included
Slovakia	SVK	✓ Included	✓ Included
Denmark	DNK	✓ Included	✓ Included
Brazil	BRA	✓ Included	✓ Included
Latvia	LVA	X	✓ Included
Lithuania	LTU	X	✓ Included
Sweden	SWE	✓ Included	✓ Included
Finland	FIN	✓ Included	✓ Included
South Africa	ZAF	✓ Included	✓ Included
France	FRA	✓ Included	✓ Included
Greece	GRC	✓ Included	✓ Included
United Kingdom	GBR	✓ Included	✓ Included
Luxembourg	LUX	✓ Included	✓ Included

Italy	ITA	✓ Included	✓ Included
Mexico	MEX	✓ Included	✓ Included
China	CHN	✓ Included	✓ Included*
United States	USA	✓ Included	✓ Included
Poland	POL	✓ Included	✓ Included
Netherlands	NLD	✓ Included	✓ Included
South Korea	KOR	✓ Included	✓ Included

*included but not the same

Included industries

Electricity and gas
Basic metals
Mining non-metals
Chemicals
Refined oil products
Mining energy
Construction
Plastics
Other manufacturing
Food
Paper products
Mining non-energy
Textiles and clothing
Machinery
Electronics
Metal products
Motor vehicles
Electrical equipment
Wood products
Mining support activities
Other transport equipment

Appendix E Disclaimer

AI tools were employed during the writing process of this thesis solely to enhance spelling, grammar, and readability. The content, analysis, and conclusions remain entirely my own.