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**Beyond Territorial Emissions: Pricing Policies,
Embodied Carbon, and Green Innovation in OECD
Countries**

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*To my parents,
whose sacrifices paved the path to my dreams,
and who believed in me when I was still searching for my way.
Making you proud was the promise I constantly repeated to myself throughout this journey.
I owe, and will always owe, my greatest victories to you.
Above all, this milestone is yours.*

*To those who walk by my side
and those who protect me from afar,
thank you for every little gesture that made a difference.*

*And lastly, to myself:
May this always be a reminder
to be fearless,
bet on yourself,
and never stop growing.*

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Introduction

Between 1995 and 2023, while domestic emissions in OECD countries fell by 9.9%, consumption-based emissions dropped by only 3%, a gap that not only has never been closed but has nearly doubled. Understanding how this is possible is the central question underlying this thesis.

When a country introduces carbon pricing mechanisms, the most polluting industries tend to relocate to economies with laxer regulations, shifting emissions through imports; as a result, that country appears cleaner in official records, but its actual impact on the climate remains unchanged or changes only marginally.

Although carbon pricing is spreading rapidly and is projected to cover 27% of global emissions among OECD countries by 2023, its effectiveness is still assessed almost exclusively using territorial emissions, which is precisely the metric on which leakage acts.

The existing literature, such as Best et al. (2020) and Döbbeling-Hildebrandt et al. (2024), has already extensively examined the effect of carbon pricing on territorial emissions; however, few studies have simultaneously estimated the impact on both production and consumption emissions across a broad sample of OECD countries in the long term, and none have tested the moderating role of innovation on both dimensions.

This is what this thesis sets out to examine: a balanced panel of 36 OECD countries, from 1995 to 2023, with 1,044 observations, measuring carbon pricing both in terms of the presence of the policy (dummy variables) and price intensity, with green patents as a measure of innovation; and organized around three hypotheses: the effect on production-related emissions, the impact on consumption-related emissions, and the moderating role of green innovation.

The analysis addresses these issues in order, with Chapter 1 defining the theoretical framework covering both dimensions, defining carbon leakage, explaining carbon pricing instruments, and linking them to innovation, as well as formulating the three hypotheses. Building on this, Chapter 2 describes the sample, the variables, and the empirical strategy. Finally, Chapter 3 estimates and discusses the results related to the three hypotheses.

Chapter 1 – Carbon Pricing and CO₂ Emissions: Theory and Literature Review

1.1 Production-Based vs. Consumption-Based Emissions

Is it possible for a country to decrease its own emissions while simultaneously contributing to an increase in global emissions? The answer is yes, and this apparent contradiction stems from the methodology employed in measuring CO₂ emissions.

CO₂ emissions are officially calculated using the Production-Based Emissions (*EP*) system, which attributes emissions to the country where goods are produced and where combustion physically takes place. This is the indicator used by all major international climate agreements, such as the IPCC, the UNFCCC, and the Kyoto Protocol, to define international climate goals (Peters et al., 2011).

Consequently, climate policies and Emissions Trading Schemes (ETS), mechanisms designed to combat global warming, are also based on this system.

In their paper “Consumption-Based Accounting of CO₂ Emissions”, Davis & Caldeira (2010) argue that although the *EP* system is verifiable and standardized, in a global economy, production and consumption are geographically separated; in fact, *EP* attributes emissions to the producing country without considering who is driving the demand for production, and today, these activities often do not take place in the same country.

To illustrate: a Chinese company supplying the European market produces emissions that the *EP* attributes entirely to China, even though it is European demand that determines the very existence of that company.

In response to this limit, the authors apply the Consumption-Based Emissions (*EC*) framework, which attributes emissions to the country of final demand throughout the entire supply chain, regardless of where production physically occurs.

Formally, consumption-based emissions are calculated from Production-Based Emissions by adjusting for the emissions embedded in international trade.

$$EC_r = EP_r - EEE + EEI$$

where *EEE* (Emissions Embodied in Exports) represents the emissions generated domestically within the country *r* to produce goods shipped abroad, and *EEI* (Emissions

Embodied in Imports) captures the emissions generated outside the country r to produce goods consumed domestically.

It follows that countries where EC exceeds EP ($EC > EP$) are net importers of emissions, meaning they consume more than they produce; this is the case for the United States, Japan, and the majority of Western Europe. Conversely, countries where EP exceeds EC ($EC < EP$), such as China, Russia, and India, are net exporters, generating emissions on behalf of foreign consumers.

Calculating Consumption-based emissions requires MRIO (Multi-Regional Input-Output) models, which trace emissions across the entire global supply chain, attributing them to the country of final consumption.

Emissions embedded in internationally traded goods are referred to as Emissions Embodied in Trade (EET) and represent the amount of CO₂ transferred from one country to another, hidden within the traded products.

The magnitude of the gap between EP and EC was first highlighted by the authors, who found that in 2004, approximately 6.2 Gt of CO₂ were emitted during the production of goods ultimately consumed in a different country, representing 23% of all global CO₂ emissions from fossil-fuel burning, and therefore not captured by national territorial inventories.

In 2004, and still today, China was the world's largest emitter of territorial CO₂, but the most striking fact is that of all the CO₂ it produced, 22.5%, specifically 1.4 Gt of CO₂, was not intended for its own citizens but rather for consumers in other countries.

On the receiving end, net imported emissions accounted for 10.8% of United States consumption-based emissions, 17.8% in Japan, and between 20% and 50% across Western Europe.

A particularly revealing case is Norway, Switzerland, and Sweden, whose clean domestic energy mix results in low EP , yet per capita EC ranges from 10.5 to 12.5 tons, driven by affluent lifestyles and demand for goods produced abroad with carbon-intensive energy. These cases illustrate why EP alone is an insufficient measure.

The gap documented by Davis & Caldeira in 2004 was not static; it was growing. Peters et al. (2011) showed that between 1990 and 2008, emissions embedded in international trade increased at 4.3% per year, faster than global GDP (+3.6%/year), total CO₂ emissions

(+2.0%/year), and population (+1.4%/year). More precisely, rising from 4.3 Gt in 1990, representing 20% of global emissions, to 7.8 Gt in 2008 (26%).

The consequences of this trend became particularly evident when examined against the Kyoto Protocol, which requires developed countries (Annex B) to cut production emissions by 5% relative to 1990, while developing nations (non-Annex B) had no obligations.

In this period, Annex B countries reduced their *EP* by approximately 2%. Over the same period, however, net emission transfers from non-Annex B to Annex B nations grew from 0.4 Gt to 1.6 Gt, exceeding the Kyoto Protocol reduction target by approximately 130%. In total, international trade relocated 16 Gt CO₂ from Annex B to non-Annex B countries over the entire period. Moreover, in terms of *EC*, 11% of global emission growth (1990-2008) is attributed to Annex B consumption, further highlighting the limitations of territorial accounting.

The authors also found that China accounted for 55% of global *EP* growth over the same period, with 75% of the growth in Annex B consumption-based emissions attributable to Chinese production. Notably, while territorial accounting places China as the world's largest emitter, followed by the United States, a shift to consumption-based accounting reverses this ranking, with the United States returning to first place.

Over the years, this growth has continued unabated: forecasts for 2024 estimate that global fossil fuel emissions will reach 37.4 Gt, representing a 0.8% increase from 2023 and a 1.3% increase from 2022 to 2023, while atmospheric CO₂ levels will be 52% higher than pre-industrial levels (Friedlingstein et al., 2025). This suggests that the trend documented by Peters et al. shows no sign of reversal.

The economic mechanism that explains this divergence is the so-called “carbon leakage”.

1.2 Carbon Leakage

As shown by Schroeder & Stracca (2025), when a country decides to implement climate policies, companies operating within it tend to shift their production to countries with fewer environmental policies. This phenomenon is known as “carbon leakage” and occurs in three main steps:

It all starts when a country adopts or intensifies climate policies, thereby increasing marginal production costs for emission-intensive industries. Consequently, companies within that country face an international competitive disadvantage, as they compete against international producers who do not incur the same costs. Secondly, two phenomena may emerge: firms shift production or new investments to jurisdictions with weaker regulations, or, the most significant in the short term, consumers and downstream industries replace domestic production, which has become more expensive, with imports from unregulated countries. Finally, Production-based emissions in the country implementing the policy decline, but emissions embedded in imports rise, and simultaneously, consumption-based emissions remain stable or increase.

These effects are tangible: between 1990 and 2018, net imported emissions rose steadily in the Annex B countries under the Kyoto Protocol, while they fell in non-Annex B countries, particularly China and India. This proves that countries that have committed to reducing emissions have seen their *EP* fall, but their *EC* have remained high because part of the emissions-intensive production has shifted elsewhere.

Not all carbon leakage is the same. Copeland & Taylor (2004) identified two different theories regarding the intensity of this phenomenon and the extent to which environmental regulation influences international trade flows. The Pollution Haven Effect (PHE) describes a moderate effect supported by empirical evidence and endorsed by the authors; it argues that carbon leakage is real but has a marginal effect, secondary to elements such as factor endowments, technology, transportation costs, and economies of scale. The Pollution Haven Hypothesis (PHH), on the other hand, is the stronger version but empirically weaker; it views environmental regulation as the dominant effect, causing high-emission production to migrate to countries with low regulation, overriding all other factors that determine trade flows and rendering national climate policies ineffective in preventing this shift.

Therefore, the authors suggest that leakage exists but is limited. However, this finding must be viewed in the context of its time, based on data from the 1990s, when carbon prices were practically nonexistent and climate policies were still weak. With today's rising prices, the empirical question remains open.

The extent to which carbon pricing policies lead to carbon leakage has been directly addressed in recent empirical literature. In particular, two studies provide evidence at complementary scales: one macroeconomic and one sectoral.

Schroeder & Stracca (2025) estimate the effect of carbon taxes on both Production-based emissions and consumption-based emissions using a panel of 57 countries from 1991 to 2018. The authors show that countries that have introduced carbon taxes, which are national taxes on emissions, have reduced *EP* gradually and significantly by about 7%, stabilizing approximately 6 years after implementation, and that each additional dollar of carbon tax per ton of CO₂ reduced territorial emissions by about 0.07%. The effect on *EC*, instead, is smaller and statistically insignificant. This provides evidence of carbon leakage: the domestic reduction does not translate into a global reduction.

The most important finding concerns trade openness: countries with low trade openness experience a significant reduction in both *EP* and *EC* due to carbon taxes, while countries with high trade openness see carbon taxes reduce *EP* but not *EC*, with this divergence becoming statistically significant approximately six years after implementation. The conclusion is that leakage is proportional to trade integration; therefore, in open economies, a carbon tax is effective in reducing domestic emissions but ineffective in reducing global emissions.

Unlike the national carbon tax, price changes in the European Union (EU) ETS, a supranational emissions trading system, significantly reduce both *EP* and *EC*, lowering them by approximately 0.5% of the emissions growth rate for every 1% increase in price. In this case, leakage does not occur because there is no cost asymmetry among producers from different countries within the same system.

Teusch et al. (2024), instead, analyze 3,295 cement, steel, and aluminum facilities across 140 nations using monthly data from 2015 to 2021. In this time, the global average carbon price across all plants in the sample, including those with a zero price, rose from USD 1.4 to USD 10.9 per ton of CO₂ equivalent (tCO₂e), and facilities already subject to regulation in 2015 experienced a price increase from USD 8 to USD 64/tCO₂e.

Additionally, price disparities between trading partners grew by more than 350% during the period under review; this disparity greatly increases the incentive to shift manufacturing to unregulated nations, thereby raising the risk of carbon leakage.

On the territorial level, unregulated facilities experienced over a 10% increase in their *EP*, while regulated facilities kept their emissions stable. Supporting this, the authors show that a \$1/tCO₂e increase leads to an average 1.3% reduction in emissions for cement and steel.

On a trade level, a \$1/tCO₂e increase in the price asymmetry between importing and exporting countries raises the emissions embedded in imports by 0.3% for steel and 4.6% for cement. Since cement is rarely traded internationally, even small volume changes cause significant percentage shifts, leading to a leakage rate of 23% for cement, 3.4% for steel, and an overall average of 13%. This estimate exceeds previous empirical studies on the EU ETS but aligns with the mid-range of theoretical modeling studies, which typically predict carbon leakage rates between 5% and 30%.

Therefore, these studies converge on the common conclusion that leakage exists and can be measured, but that its intensity depends on the type of instrument adopted and the country's level of trade openness.

These findings raise a natural question: if carbon leakage arises from cost asymmetries between regulated and unregulated producers, can it be neutralized at the border without requiring global coordination on carbon pricing? The European Parliament and Council of the European Union (2023) found a response with the Carbon Border Adjustment Mechanism (CBAM), introduced gradually through reporting requirements starting in October 2023 and fully operational since January 2026, with plans to extend it to all EU ETS sectors by 2030.

The sectors covered are cement, electricity, fertilizers, iron and steel, aluminum, and hydrogen. It requires importers to purchase certificates equivalent to the emissions embedded in the imported goods. The price of these permits is based on the weekly average auction price of EU ETS allowances, ensuring that overseas producers incur the same carbon cost as European producers. Furthermore, if one of the foreign producers has already paid a carbon price in their country of origin, they can subtract that amount from the number of certificates they are required to surrender.

Although revolutionary as a response to carbon leakage, it has a single limitation: it acts only on the import side, not on the export side. Consequently, a European industry that exports to countries without carbon pricing remains at a competitive disadvantage compared to local producers in those markets, and the Regulation itself acknowledges this problem but, for now, leaves it unresolved.

1.3 Carbon Pricing Instruments

The theoretical justification for imposing a price on emissions lies in the need to correct a fundamental market failure: the negative externality. Pigou, in *The Economics of Welfare* (1932), explained that when producers make goods or provide services, they may cause effects that harm third parties who are not involved in the transaction, and for which the producer is neither compensated nor penalized. Thus, the author identifies a particular type of market failure arising from the disparity between marginal private net product and marginal social net product. Because the producer does not account for these negative effects on its internal costs, the private cost is lower than the full social cost. Pigou used industrial smoke as the main example, arguing that factory emissions impose real but unpaid costs on the community.

In order to fill this gap, he suggests that governments impose what he terms extraordinary restraints or encouragements, such as taxes or bounties. This idea served as the foundation for the now-called Pigouvian tax, which was the precursor to modern carbon pricing schemes and was intended to correct market behavior by internalizing environmental costs.

According to Best et al. (2020), the two main tools currently used as carbon pricing mechanisms to achieve climate neutrality are the carbon tax and the ETS (Emissions Trading System), which ensure that emitters internalize the social cost of their emissions.

The world's first carbon tax was introduced in 1990 by Finland. It is a direct tax on CO₂ emissions, or equivalently on the carbon content of fuels. When the government sets a price per ton of CO₂ emitted, every firm subject to the tax must compare this cost with its own abatement costs. Generally, the company decides to reduce emissions if doing so costs less than the tax; otherwise, it pays the tax. Consequently, reductions occur where the abatement cost is lowest, meaning where carbon pricing is considered less intrusive than direct regulation, as it leaves the choice of abatement method to the market (Best et al., 2020).

The ETS is defined by the OECD (2024b) as the price of tradable emission permits in mandatory emissions trading and cap-and-trade systems, representing the opportunity cost of emitting an additional unit of CO₂e regardless of the method used to allocate permits. Two types are distinguished: mass-based systems, in which a cap is set on the total emissions of an industry or facility (including cap-and-trade schemes), the largest being the EU ETS; and rate-based systems, in which a cap is set on emissions intensity, with China's having the largest.

It is also used, for some countries, such as Sweden, to have both a carbon tax and participate in an ETS (Best et al., 2020). The general preference between the two leans toward ETS and continues to grow year after year; in 2023, according to the OECD (2024b), 40 countries had an ETS in place, while 27 had an explicit carbon tax.

The 2015 Paris Agreement commits signatory countries to limiting global warming to “well below 2°C above pre-industrial levels,” with a goal of 1.5°C. To achieve this objective, each participating country is required to prepare, communicate, and maintain its Nationally Determined Contributions (NDCs), national commitments to reduce emissions, which must be progressively strengthened over time.

The NDCs do not specify which policy tool to use to reduce emissions, but they do establish a political obligation to do so, driving governments to adopt explicit instruments such as carbon taxes and ETS.

Despite this acceleration, the adoption of carbon pricing remains limited and geographically uneven. The OECD (2024b) reports that, among the 79 countries analyzed, which account for approximately 82% of global greenhouse gas (GHG) emissions, only 27% of these emissions are subject to an explicit carbon price, such as an ETS or a carbon tax. Furthermore, the share of emissions subject to a positive Net Effective Carbon Rate (Net ECR) rises to 42% when fuel excise taxes, meaning implicit forms of carbon pricing, are also included. This means that 58% of global emissions are still not subject to any carbon price, not even in an implicit form. Moreover, the price level is also inadequate relative to the targets: the average Net ECR across the 79 countries in 2023 was EUR 14.0/tCO_{2e}. Even lower than the EUR 17.9/tCO_{2e} recorded in 2021, though this decline is due to increased fossil fuel subsidies in response to the 2022 energy crisis, which offset and exceeded the explicit prices set by carbon policies.

Carbon pricing is still far from the level required by the climate targets set for 2030, which, according to the Net ECR, should settle between EUR 60 and EUR 120/tCO_{2e}, being between four and nine times the current average level. Given this gap, understanding the effectiveness of the instruments already implemented, both on production and consumption emissions, becomes a matter of particular importance.

After more than three decades of experience with these types of instruments, over 70 implementations of carbon taxes and cap-and-trade systems worldwide (Döbbeling-Hildebrandt et al., 2024), and no consensus in either science or politics regarding their

effectiveness, the empirical literature has examined the efficiency of carbon pricing instruments with growing interest in recent years, and the answer, though not without nuance, is affirmative.

The first systematic cross-country study on the effectiveness of carbon pricing was conducted by Best et al. in 2020 using data spanning nearly two decades and accounting for renewable energy policies, energy system structure, economic growth, and income levels, to isolate the specific effect of carbon pricing on emissions from fuel combustion (which account for approximately 80% of human CO₂ emissions).

The most significant findings were the following. Firstly, countries with a carbon price recorded an annual growth rate in combustion emissions that was approximately 2 percentage points lower than that of countries without such policies. Second, the authors report that their effect is quantifiable based on the price level; that is, every additional euro per tCO₂ in the effective carbon price is associated with a reduction in the annual growth rate of emissions of about 0.3 percentage points. Furthermore, it has been shown that in the long term, having a carbon price is associated with per capita emissions that are approximately 12% lower after three years, equivalent to an average annual reduction of about 4%. Finally, the authors found no statistically significant differences between carbon taxes and ETS: both raise the cost of emissions and result in similar levels of reduction. In this regard, the study identifies two distinct effects: a regime effect, whereby the mere existence of a carbon price impacts emissions regardless of its level, and a level effect, by which higher prices correspond to greater reductions.

Even more recent is the study conducted by Döbbeling-Hildebrandt et al. in 2024. Their meta-analysis finds that the introduction of a carbon price produced immediate and significant reductions in emissions in at least 17 of the 21 schemes analyzed worldwide, and that among these, statistically significant reductions range from -5% to -21%, with an average effect of -10.4%. After adjusting for publication bias, which tends to overrepresent studies with large and significant effects, the range narrows to between -4% and -15%, with an average effect of -6.8%, still representing a substantial reduction. Specifically: EU ETS - 7.3%, British Columbia (BC) carbon tax -5.4%, and Chinese ETS pilots -13.1%.

The most interesting result emerges from the heterogeneity of effects across the different schemes: using Bayesian model averaging (BMA), the authors test which factors, such as the choice between a carbon tax and an ETS, the price level, or sectoral coverage, explain

the variation in effects. The result is that in all cases, the Posterior Inclusion Probability (PIP) is less than 0.5, making none of these factors statistically significant. What matters most, instead, is the specific institutional context of the individual scheme and the duration of its implementation; therefore, effectiveness would depend not so much on the type of instrument as on how it is designed and how long it has been in force.

Both studies agree that carbon pricing reduces *EP* in a measurable, robust, and significant way. However, as previously shown, a reduction in *EP* does not equate to a reduction in emissions in open economies; indeed, it may be accompanied by an increase in *EEI* (embedded emissions in imports), leaving *EC* unchanged or even increasing.

1.4 The Role of Innovation

The previous section showed how carbon pricing reduces *EP* through a direct price effect. However, there is an additional channel through which environmental regulation operates, a structural mechanism that alters not only emission levels but also the technological trajectory of the countries that adopt it: technological innovation.

Porter & van der Linde (1995), in what would become known as the Porter-Linde Hypothesis, claim that the debate between environmental regulation and competitiveness has historically been framed incorrectly. The traditional view treats it as a fixed trade-off, based on a static model in which technology, production processes, and customer needs are constant, and where every additional environmental constraint inevitably translates into higher costs for firms and a loss of competitiveness in international markets.

Their study notes that this framework does not describe how the international economy functions, as it is dynamic and based on the capability to innovate continuously. Competitiveness does not stem from the lowest input costs or the largest production scale, but from the ability to improve and innovate in a sustained manner.

Additionally, not all environmental regulations have the same effect on innovation. They can be grouped into two approaches. On one hand, command-and-control regulations mandate specific technologies and lead to what the authors call “best available technology”, that is, once a company has adopted the mandated technology, the incentive to seek better solutions disappears. On the other hand, market-based instruments, including pollution taxes

and tradable permits, give companies the freedom to choose how to respond to the constraint, creating incentives for continuous innovation and boosting resource productivity.

Carbon pricing is exactly this type of instrument: it sets a price on emissions without prescribing how to reduce them, allowing the market to choose the most efficient method, which can be, and often is, technological innovation (Lim & Prakash, 2023).

Porter & van der Linde also emphasize that stricter regulations tend to generate more innovation than more permissive ones; they require more fundamental solutions, while weaker ones can be managed incrementally with an “end-of-pipe” solution. Although compliance costs may rise with stricter regulations, the innovation potential grows even faster.

The impact of innovation extends beyond the borders of the country that adopts the policy. In this regard, the authors demonstrate that countries that introduce stringent environmental regulations before others develop technological expertise that translates into competitive advantages in international markets. Germany, for instance, by being the first in Europe to introduce packaging standards, gave its companies an edge in international markets; the same applies to cases such as Scandinavian paper and pulp producers, as well as to Cummins Engine in the United States with the development of low-emission diesel engines. Carbon pricing is therefore not merely a tool for reducing emissions, but potentially a catalyst for technological transformation with implications for the country’s overall competitiveness.

For decades, direct cross-national empirical evidence has been limited or inconclusive. Lim & Prakash (2023) fill this exact gap, providing the first systematic test of the Porter-Linde Hypothesis and confirming that carbon pricing is a market-based, rather than a technology-forcing, regulation.

The analysis examines a balanced panel of 38 OECD countries over a 34-year period, representing the most extensive cross-national panel available on this topic, with the number of patent applications per million inhabitants as the dependent variable and carbon pricing as the key independent variable. The authors use two measures: All Climate Patents, i.e., all climate-related patents, and Quality Climate Patents, which include only patents filed in at least two jurisdictions and are therefore of greater technological and commercial value.

The outcomes for the first category in the short-term show that the adoption of carbon pricing is associated with an increase of 3.1 patent applications per million inhabitants in the year of

adoption, while, in the long term, the effect is 5.2 patents per million inhabitants. The result is also significant for Quality Climate Patents; in particular, the adoption of carbon pricing is associated with an increase of 0.816 quality patents per million in the year of adoption, and 2.766 in the long term.

The findings pass three robustness tests. The first concerns carbon leakage: even controlling for the possibility that firms might shift production abroad, the relationship between carbon pricing and innovation remains positive and significant. Second, the effect is not attributable to the presence of complementary climate policies on renewables. Finally, carbon pricing stimulates private innovation regardless of how much the government invests in low-emission R&D.

Furthermore, a two-stage mechanism linking carbon pricing to structural emissions reductions is identified: Initially, when a country adopts carbon pricing, firms subject to the policy begin to devote attention and resources to emissions-related technologies to find ways of reducing the cost that the policies associate with emissions; this is what the authors call compliance efforts. In the second stage, this focus translates over time into concrete climate-related technological innovations, such as new patents, processes, and solutions; the need to produce less transforms into structurally different, cleaner production.

The authors are explicit in stating that their argument does not claim that any regulation automatically leads to innovation in any context, but rather that innovation is likely to occur when firms and the country can seize opportunities for innovation. For this reason, not all countries respond to the same regulation with the same level of innovation.

They show that carbon pricing stimulates innovation regardless of public spending on R&D. Building on this, it can be argued that green innovation capacity moderates the intensity of this response: a country with a higher level of environmental patent activity possesses a more robust infrastructure of technological expertise, connections between industry and research, and the capacity to absorb new technologies; conversely, in countries with lower green innovation capacity, carbon pricing may reduce *EP* primarily through a contraction in productive activity, without generating structural technological change.

1.5 Research Question and Hypotheses

The empirical literature has consistently shown that carbon pricing instruments such as carbon taxes and emissions trading systems (ETS) reduce Production-based emissions (*EP*) in countries that adopt them. Specifically, Best et al. (2020) find that countries with carbon pricing have territorial emissions growth rates approximately 2 percentage points lower than others; Döbbeling-Hildebrandt et al. (2024) confirm significant reductions ranging from 5% to 21% across 17 out of 21 carbon pricing schemes.

There is no doubt, therefore, that carbon pricing works on *EP*, also because almost all the literature focuses exclusively on the latter. But, as Davis & Caldeira (2010) and Peters et al. (2011) note, in a global economy, a reduction in domestic emissions does not necessarily equate to a reduction in global emissions; in fact, due to the phenomenon of carbon leakage, emissions can simply shift elsewhere through international trade. This means that assessing the effectiveness of carbon pricing by looking only at *EP* is potentially misleading: a country may appear clean on paper while its consumption-based emissions (*EC*) remain unchanged or increase. The few studies that examine the effect of carbon pricing on *EC*, such as Schroeder & Stracca (2025) and Teusch et al. (2024), agree that the actual effectiveness of carbon pricing, measured in global terms, is overestimated in the existing studies.

The literature has also explored the innovation channel: Porter & van der Linde (1995) argue that well-designed environmental regulation stimulates innovation rather than hindering it; Lim & Prakash (2023) confirm that carbon pricing increases climate technology patents by +3 patents per million inhabitants in the short term and +5 in the long term. However, no study has yet systematically tested whether this innovative capacity moderates the effect of carbon pricing on emissions, that is, whether in countries with higher green innovation capacity, carbon pricing is more effective in reducing both *EP* and *EC*.

Despite this wealth of data, no analysis so far has examined the effect of carbon pricing on both *EP* and *EC* across a large sample of OECD countries over an extended period simultaneously, nor has the moderating role of green innovation been empirically verified in this context.

It is precisely this gap that this study aims to bridge. Specifically, it seeks to analyze whether carbon pricing instruments, specifically carbon taxes and emissions trading systems, genuinely reduce global CO₂ emissions in OECD countries or if they merely shift the burden

elsewhere, and whether this effect differs in countries with greater capacity for green innovation.

Starting from this question, the research articulates three empirical hypotheses:

The first one concerns the effect of carbon pricing on territorial emissions:

H1: Carbon pricing instruments are associated with a statistically significant reduction in production-based CO₂ emissions (EP).

This result is expected based on established literature: Best et al. (2020) and Döbbeling-Hildebrandt et al. (2024) show significant reductions in territorial emissions in countries that adopt carbon pricing instruments.

The second hypothesis concerns the effect of carbon pricing on consumption emissions:

H2: The effect of carbon pricing on consumption-based CO₂ emissions (EC) is weaker or statistically insignificant, consistent with the presence of carbon leakage through international trade.

If carbon pricing reduces domestic production of carbon-intensive goods without affecting final demand, emissions do not disappear but are shifted to countries with less stringent regulations, becoming embedded in imports, as shown by Schroeder & Stracca (2025) and Teusch et al. (2024).

The third hypothesis introduces the moderating role of innovation:

H3: The emission-reducing effect of carbon pricing is amplified in countries with higher green innovation capacity, as measured by environmental patent activity.

As introduced by Porter & van der Linde (1995), who provide the theoretical framework, and Lim & Prakash (2023), who confirm these effects particularly in the long run, in countries with greater innovative capacity, firms can respond to carbon pricing by investing in cleaner technologies, reducing emissions structurally rather than relocating production.

Chapter 2 – Data and Methodology

The arguments developed in Chapter 1 converge on a single empirical question: whether the effect of carbon pricing on emissions survives the adjustment for international trade. Answering it requires moving from theory to evidence, from what carbon pricing should do, to what it can be observed doing across countries and over time. This chapter describes the data and the empirical strategy that make this transition possible.

2.1 Data and Sample

Because carbon pricing instruments have been adopted at different times and in different countries, testing the impact on emissions requires data that varies both across nations and over time. Panel data is, therefore, the natural structure for this work.

In particular, the research is based on a balanced panel of 36 OECD countries observed from 1995 to 2023, yielding 1,044 country-year observations.

This time series (1995–2023) is comprehensive and captures the entire lifecycle of many instruments, from their adoption to the first long-term evaluations.

The decision to not analyze all countries worldwide, but to focus solely on those belonging to the Organization for Economic Co-operation and Development (OECD), is not arbitrary; in fact, these countries not only provide the highest quality and coverage of data across all variables, but also account for nearly all carbon pricing instruments implemented globally: in the sample, 20 out of 36 countries have adopted a carbon tax, 29 out of 36 have had an active ETS, while four countries (Costa Rica, Israel, Turkey, United States) have not adopted any carbon pricing instrument for the entire period and serve as a natural control group.

Of the 38 OECD member countries, 36 are included in the analysis because a country was retained if it had non-missing data for at least 80% of the reference period for each key variable and if it showed variation in the main regressors. Consequently, Iceland and Norway have been excluded for a specific reason: the public source providing national-level consumption-based emissions data does not cover Iceland and has partial coverage for Norway (starting in 2003). Since *EC* is one of the central dependent variables of the study, their exclusion is necessary to ensure the compatibility of the two models.

The dataset includes 13 variables in total, including 10 analytical, organized into three groups according to their role in the analysis: dependent variables, which capture the two

measures of CO₂ emissions that the model seeks to explain; policy variables, which represent the carbon pricing instruments of interest; and control variables, which account for macroeconomic factors that influence emissions independently of carbon pricing policy. The dataset also includes a measure of green technology innovation, which plays a dual role in the analysis, serving both as a dependent and a moderating variable.

Central to the analysis are the two dependent variables, Production-based emissions (*EP*) and Consumption-based emissions (*EC*). Both are derived from Our World in Data (2024) and contain no missing values in the sample.

The first, *EP*, as already explained, measures CO₂ emissions physically produced within a country's territorial borders; it is expressed in tons and is the standard metric for international climate agreements and most of the existing literature. *EP* will be the dependent variable of the first model, and testing its relationship with carbon pricing instruments corresponds to testing *H1*.

The second, *EC*, measures CO₂ emissions attributable to the final country regardless of where production physically occurred, and testing its effect will correspond to verifying Hypothesis *H2*. It is calculated by adjusting *EP* for emissions embedded in international trade: adding those embedded in imports and subtracting those embedded in exports. *EC* will be used as the dependent variable in the second model and represents one of the main original contributions of this thesis compared to the existing literature.

Policies constitute the second group of variables. Carbon taxes and ETSs have no missing values and are sourced from the World Bank Carbon Pricing Dashboard (World Bank, 2024b), which tracks the history of the implementation of all these instruments worldwide. They will be treated as dummy variables, Carbon Tax dummy (*CT_d*), ETS dummy (*ETS_d*), i.e., binary variables that take the value 1 for every country-year in which a carbon pricing mechanism is in effect, and 0 otherwise. Notably, for European Union member countries, the ETS will be equal to 1 starting in 2005, coinciding with the launch of the EU Emissions Trading System.

In addition to the two binary dummy variables indicating the presence of the policy instrument, the dataset includes two continuous variables that measure the intensity in terms of effective price: Carbon Tax price (*CT_p*) and ETS price (*ETS_p*). Both are expressed in U.S. dollars per ton of CO₂ (USD/tCO_{2e}) and are drawn from the World Bank Carbon Pricing Dashboard (World Bank, 2024b). These variables directly capture the price signal that firms

receive, which is the theoretical mechanism through which carbon pricing influences production decisions.

Specifically, the Carbon Tax price is the official carbon tax rate expressed in USD/tCO_{2e}, with a value of zero for countries that have not adopted the tax. In the sample, it ranges from 0 to approximately 169 USD/tCO_{2e}, with Sweden recording the highest values.

Meanwhile, the ETS price is the market price of emission allowances in the ETS, with a value of zero for countries without an Emissions Trading System. In the sample, it ranges from 0 to approximately 99 USD/tCO_{2e}, with the highest values concentrated in European countries in the years 2022-2023.

For these two indicators, a value of zero reflects the absence of the policy in that country-year, whereas for some of these, where the pricing mechanism was active but price data was unavailable, the cell was left blank; this is the case for Latvia, Slovenia, Switzerland, Mexico, and New Zealand, for a total of 29 observations (19 missing for Carbon Tax price and 10 missing for ETS price).

Finally, the database includes three control variables: GDP per capita, Industry Value Added, and Alternative and Nuclear Energy.

Specifically, GDP per capita (*gdp_{pc}*) in current USD is taken from the World Bank (2024c) and has no missing values. It is included in the model as a control for income level and the economic cycle: during expansions, emissions tend to increase, while during recessions they tend to decrease.

Industry Value Added (*ind*) as a percentage of GDP comes from the World Bank (2024d) and measures the carbon intensity of a country's economic structure, controlling for the deindustrialization process that many OECD countries underwent during the period covered by the database: a more industrialized economy systematically emits more under otherwise equal conditions.

The Alternative and Nuclear Energy (*eng*) indicator, expressed as a percentage by the World Bank (2024a), has no missing values and represents the share of alternative and nuclear energy in total energy use: countries that have invested in clean energy independently of carbon pricing tend to have lower emissions.

Finally, the Green Patents (*GreenPat*) variable measures patent activity in environmental technologies, expressed as inventions per million inhabitants; it serves as a measure of green innovation output at the country level. Sourced from the OECD (2024a), it covers 98% of the sample with only 21 missing values, concentrated in Costa Rica (10 years), Latvia, Lithuania, and Estonia (3-4 years each).

2.2 Descriptive Analysis

Before analyzing the relationships between the variables, it is helpful to examine their distribution and scale within the sample.

Table 1. Descriptive Statistics for the OECD Panel Sample (1995-2023)

Variable	N	Mean	Std. Dev.	Min	Median	Max	Unit
<i>EP</i>	1044	360.10	922.23	4.67	72.33	6126.90	MtCO ₂
<i>EC</i>	1044	404.50	974.70	6.17	100.83	6656.01	MtCO ₂
<i>CT_d</i>	1044	0.26	0.44	0	0	1	0/1 dummy
<i>ETS_d</i>	1044	0.47	0.50	0	0	1	0/1 dummy
<i>CT_p</i>	1025	8.19	24.57	0	0	168.83	USD/tCO ₂ e
<i>ETS_p</i>	1034	11.48	21.11	0	0	98.56	USD/tCO ₂ e
<i>gdp_{pc}</i>	1044	30562.78	22109.08	2182.69	26087.61	134965.80	USD
<i>ind</i>	1035	25.09	5.22	9.11	25.34	40.76	% of GDP
<i>eng</i>	1044	14.85	12.98	0	11.68	51.45	% of total energy use
<i>GreenPat</i>	1023	16.60	20.69	0.01	9.30	147.48	Inventions per million residents

Note. *EP* and *EC* are rescaled to million tonnes (Mt) for readability. *gdp_{pc}* is expressed in current USD to account for inflation. The lower N for *CT_p* and *ETS_p* reflects 29 country-years in which the policy was active, but the price was not available in the source.

Sources. Our World in Data (2024); OECD (2024a); World Bank (2024a, 2024b, 2024c, 2024d).

Since the sample includes very different economies, ranging in size from Luxembourg's approximately 10 Mt to the United States' over 6,000 Mt, the first thing this table highlights is the enormous standard deviation relative to the mean: for production-based emissions, the

standard deviation is 922 Mt compared to an average of 360; while for consumption-based emissions it is 975 Mt compared to 404 Mt.

The variation is equally significant for carbon policies: the CT_d takes a value of 1 in 25.6% of the country-years, while the ETS_d does so in 46.6%.

Finally, the same applies to the variation in *GreenPat*, which ranges from a minimum of 0.01 to a maximum of 147.48, with an average of 16.60. The standard deviation of 20.69 exceeds the mean itself, indicating a highly dispersed distribution: a small number of countries with higher green innovation intensity drive the average upward, while most countries cluster around much lower values, as confirmed by the median of 9.30.

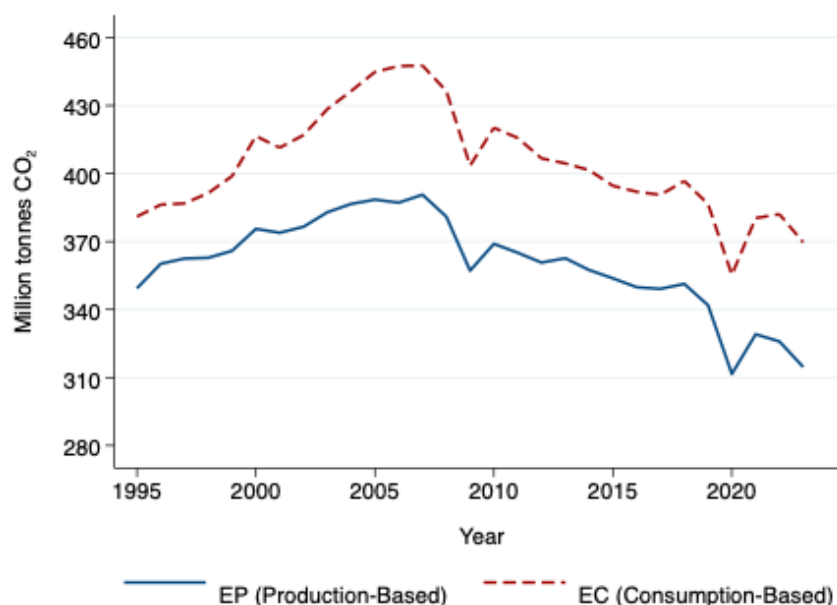
Looking at the sample overall, average territorial emissions have fallen by 9.9% between 1995 and 2023, dropping from 349.4 Mt to 314.7 Mt per country. Consumption-based emissions, meanwhile, fell much less, by only 3.0%, from 381.0 Mt to 369.6 Mt, a reduction three times smaller than that of *EP*.

The divergence between *EC* and *EP*, however, has never narrowed over time; it has nearly doubled. It rose from 31.6 Mt in 1995, equivalent to 9.1% of *EP*, to 55.0 Mt in 2023, representing 17.5% of *EP*. The gap peaked in 2006 at 60.3 Mt, coinciding with the acceleration of global trade before the 2008 financial crisis. Following the latter, the gap narrowed temporarily but never returned to 1995 levels and began to widen again after 2020.

The most significant observation is that consumption emissions consistently exceed production ones in all 29 years of the sample, without a single exception; therefore, OECD countries have been net importers of emissions throughout the entire period analyzed, continuing to consume more than they produce.

This gap is consistent with the carbon leakage mechanism discussed in Chapter 1: while territorial emissions decline, a significant portion of countries' actual carbon footprint materializes abroad. This is what motivates the decision to estimate the two models separately and compare the results. Figure 1 illustrates this divergence over the entire sample period.

Figure 1. *Production-Based vs Consumption-Based Emissions: OECD Sample Average, 1995–2023*



Note. Mean values across 36 OECD countries. *EP* = production-based CO₂ emissions; *EC* = consumption-based CO₂ emissions.

Source. Our World in Data (2024).

Figure 1 confirms that, despite the overall downward trend in both series, *EC* consistently exceeds *EP*: the two series never converge structurally, and the gap remains wide throughout the entire period. This suggests that this divergence is not a temporary or cyclical phenomenon, but rather a persistent feature of the sample.

The graph also shows two sharp and simultaneous drops in both series: the first around 2008–2009, coinciding with the global financial crisis and the resulting contraction in international trade; the second in 2020, consistent with the effects of the COVID-19 pandemic. In both cases, the decline is temporary, as the *EP-EC* gap narrows momentarily before widening again. In particular, the post-2020 recovery, during which *EC* grows faster than *EP*, suggests a more pronounced rebound in embedded emissions in imports compared to territorial emissions.

To estimate the effect of carbon pricing on emissions, the model requires sufficient variation in policy indicators, both across countries and over time.

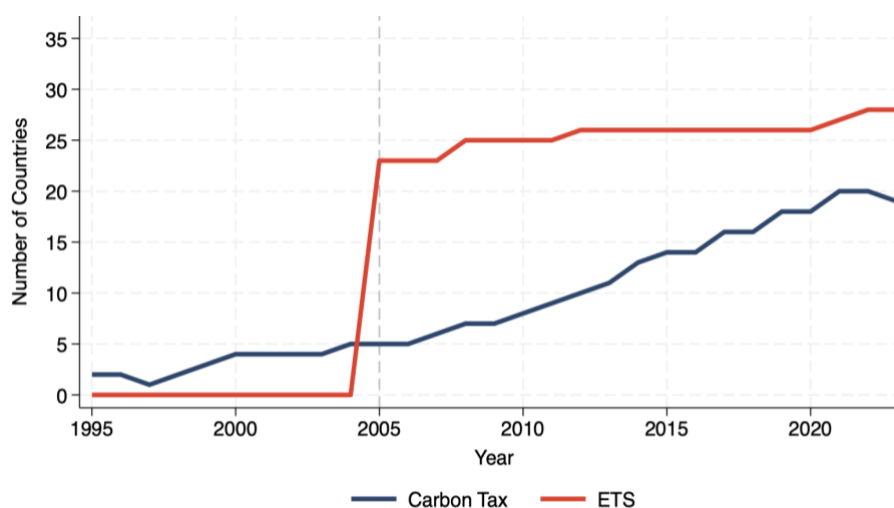
The carbon tax has been adopted gradually and in a highly fragmented manner. In 1995, only Poland and Sweden had adopted it. In the following decades, however, its growth has been slow and steady, with each country adopting the measure at different times for its own political and economic reasons. By 2023, 20 out of 36 countries had implemented it.

The ETS followed a completely different trajectory. Until 2004, no country in the sample had an active ETS. Everything changed in 2005 with a sudden surge: 23 European countries simultaneously joined the EU Emissions Trading System, the world’s largest cap-and-trade market. In the following years, other countries gradually joined, bringing the total to 28 of 36 by 2023.

Overall, in the sample, 17 countries had both a carbon tax and an ETS simultaneously, 3 had only a carbon tax (Chile, Colombia, Japan), and 12 had only an ETS, while 4 countries did not implement either (Costa Rica, Israel, Türkiye, United States).

Figure 2 and Table 2 provide a detailed overview of the year of adoption for each instrument across all 36 countries in the sample.

Figure 2. Cumulative Diffusion of Carbon Tax and ETS (1995–2023)



Source. World Bank (2024b).

Table 2. Year of Adoption of Carbon Pricing Instruments by Country

ISO	Year Carbon Tax	Year ETS	ISO	Year Carbon Tax	Year ETS
AUS	.	2012	IRL	2010	2005
AUT	.	2005	ISR	.	.
BEL	.	2005	ITA	.	2005
CAN	2019	2021	JPN	2012	.
CHE	2008	2008	KOR	.	2015
CHL	2017	.	LTU	.	2005
COL	2017	.	LUX	2021	2005

CRI	.	.	LVA	2004	2005
CZE	.	2005	MEX	2015	2021
DEU	.	2005	NLD	2021	2005
DNK	2007	2005	NZL	.	2008
ESP	2014	2005	POL	1995	2005
EST	2011	2005	PRT	2019	2005
FIN	2000	2005	SVK	.	2005
FRA	2014	2005	SVN	1999	2005
GBR	2013	2005	SWE	1995	2005
GRC	.	2005	TUR	.	.
HUN	.	2005	USA	.	.

Note. The table reports the first year of implementation for each instrument within the sample period. The symbol "." indicates that the instrument was not adopted as of 2023.

Source. World Bank (2024b).

The key variable for *H3*, Green Patents, varies considerably among the countries in the sample. The five countries with the highest average are Korea (64.56), Japan (60.12), Denmark (51.07), Germany (44.48), and Finland (35.01) inventions per million residents, all of which are technology-intensive economies. Conversely, the five countries with the lowest average are those with economic structures less oriented toward innovation, namely Colombia (0.19), Mexico (0.27), Costa Rica (0.38), Chile (0.99), and Türkiye (0.72). Overall, the sample has an average of 16.60 inventions per million residents.

2.3 Empirical Strategy

To test the three hypotheses formulated in Chapter 1, the study exploits cross-country and temporal variation in the adoption of carbon pricing instruments to estimate a single average coefficient that captures the effect on emissions.

The model is estimated separately for Production-based emissions (Model 1) and for consumption-based emissions (Model 2), reflecting the structure of the hypotheses since *H1* concerns *EP* and *H2* concerns *EC*. The comparison of the coefficients of the two models

constitutes the empirical test of carbon leakage: if Carbon Tax and ETS reduce *EP* but not *EC*, the difference between the two coefficients is a measure of the shift in emissions.

The basic model for both variables is the following:

$$\ln(Y_{it}) = \alpha_i + \delta_t + \beta_1 CT_{d_{it}} + \beta_2 ETS_{d_{it}} + \gamma_1 \ln(gdp_{pc_{it}}) + \gamma_2 ind_{it} + \gamma_3 eng_{it} + \varepsilon_{it}$$

where i denotes the country and t the year.

Y_{it} is the dependent variable, which takes the value of *EP* in Model 1 and of *EC* in Model 2. Since, as shown in Table 1, production-based and consumption-based emissions vary enormously in the sample, from 4.7 Mt to over 6,000 Mt, regression on absolute levels would produce biased estimates. The logarithmic transformation resolves this problem and offers an important interpretive advantage: the coefficients of the Carbon Tax dummy and ETS dummy become semi-elasticities, that is, the percentage change in Y associated with the adoption of the policy. Specifically, for binary policy variables, the percentage change in emissions is computed as $(e^\beta - 1) \times 100$. Coefficient estimates are rounded to three decimal places in all tables, while percentage effects reported in the text are derived from the underlying full-precision estimates.

The α_i represent country fixed effects, a constant term for each country that captures all time-invariant structural characteristics such as energy endowment, historical industrial structure, institutions, geographic location, and climate; and allows the model to isolate the effect of the policy from these structural characteristics.

By contrast, δ_t represents the year fixed effects, i.e., a constant term for each year that accounts for global shocks common to all countries in the same year, such as the 2008 financial crisis, the COVID-19 pandemic in 2020, and the 2022 energy crisis. Without these, those global declines in emissions would be erroneously attributed to carbon pricing. This two-way fixed effects approach is consistent with the methodology adopted by Best et al. (2020) in their cross-country analysis of carbon pricing efficacy.

The coefficients of the Carbon Tax dummy (CT_d) and ETS (ETS_d) dummy correspond to β_1 and β_2 ; they are the focus of the analysis and measure the average effect of the presence of the carbon tax and the ETS on emissions, controlling for all other factors. For example, if β_1 is negative and statistically significant, the carbon tax is associated with a reduction in emissions.

On the other hand, γ_1 , γ_2 , and γ_3 are the coefficients of control variables, namely income, industrial structure, and energy mix, which are necessary to isolate the effect of the policy. GDP per capita (gdp_{pc}) controls for income level and the business cycle: without it, a carbon tax implemented during a recession would appear more effective than it is, since emissions tend to rise during expansions and fall during recessions. It enters the model as a natural logarithm for the same reasons as EP and EC . Industrial value added as a percentage of GDP (ind) controls for the carbon intensity of the economic structure: a more industrialized economy systematically emits more than a service-based one, and many OECD countries underwent significant deindustrialization during the period covered by the sample. Finally, the share of alternative and nuclear energy (eng) controls for the energy mix: without it, the coefficient of the Carbon Tax dummy also captures the effect of complementary energy policies, since countries that have invested in clean energy independently of carbon pricing have lower emissions.

Finally, ε_{it} is the error term, i.e., everything the model fails to explain.

Since the binary dummies capture the presence of the policy but not its intensity, along with the baseline model, the study also applies an alternative specification in which the Carbon Tax dummy and ETS dummy are replaced by Carbon Tax price and ETS price, which capture the variation in intensity and allow for testing whether the price level also matters.

$$\ln(Y_{it}) = \alpha_i + \delta_t + \beta_1 CT_{p_{it}} + \beta_2 ETS_{p_{it}} + \gamma_1 \ln(gdp_{pc_{it}}) + \gamma_2 ind_{it} + \gamma_3 eng_{it} + \varepsilon_{it}$$

This specification runs on a slightly smaller sample due to 29 missing observations in the new variables, corresponding to country-years in which the policy was active, but the price was not available in the source.

Unlike the control variables, Green Patents is not included in the base model but plays a key and sequential role in the specifications to test $H3$.

The first model tests whether CT and ETS stimulate green innovation. The dependent variable $\ln(GreenPat_{it})$ enters the model as a natural logarithm, given the high variability in the sample, which ranges from 0.01 to 147.48 inventions per million residents. The model structure retains the same fixed effects and controls as the base model, differing only in the dependent variable, as shown by the formula:

$$\begin{aligned}
& \ln(\text{GreenPat}_{it}) \\
& = \alpha_i + \delta_t + \beta_1 CT_{dit} + \beta_2 ETS_{dit} + \gamma_1 \ln(gdp_{pc_{it}}) + \gamma_2 ind_{it} + \gamma_3 eng_{it} \\
& + \varepsilon_{it}
\end{aligned}$$

The second specification, instead, examines whether the effect of carbon pricing on emissions is amplified in countries with higher levels of green innovation. The dependent variable returns to EP and EC, but with the addition of the interaction term $\ln(\text{GreenPat}_{it})$ as a moderator variable in the formula:

$$\begin{aligned}
\ln(Y_{it}) = & \alpha_i + \delta_t + \beta_1 CT_{dit} + \beta_2 ETS_{dit} + \beta_3 CT_{dit} \times \ln(\text{GreenPat}_{it}) \\
& + \beta_4 ETS_{dit} \times \ln(\text{GreenPat}_{it}) + \beta_5 \ln(\text{GreenPat}_{it}) + \gamma_1 \ln(gdp_{pc_{it}}) \\
& + \gamma_2 ind_{it} + \gamma_3 eng_{it} + \varepsilon_{it}
\end{aligned}$$

As with the base model, this specification is also estimated using actual prices rather than dummy variables, to test whether not only the presence but also the intensity of carbon pricing moderates the effect of green innovation on emissions, using the following formula:

$$\begin{aligned}
\ln(Y_{it}) = & \alpha_i + \delta_t + \beta_1 CT_{pit} + \beta_2 ETS_{pit} + \beta_3 CT_{pit} \times \ln(\text{GreenPat}_{it}) \\
& + \beta_4 ETS_{pit} \times \ln(\text{GreenPat}_{it}) + \beta_5 \ln(\text{GreenPat}_{it}) + \gamma_1 \ln(gdp_{pc_{it}}) \\
& + \gamma_2 ind_{it} + \gamma_3 eng_{it} + \varepsilon_{it}
\end{aligned}$$

In terms of estimation, unlike the two interaction specifications just described, which are estimated only in their most comprehensive form with both country and year fixed effects, all other models, meaning the baseline models for *EP* and *EC*, the alternative specification with prices, and the model with Green Patents as the dependent variable, are run in three progressive specifications to show how the coefficient changes as control variables are added. The first specification does not include fixed effects and serves as a baseline, showing the raw correlation between carbon pricing and emissions without controlling for anything. The second includes only country fixed effects, controlling for structural differences between countries but not for time-specific shocks. Finally, the third specification is the most comprehensive and robust, as it includes both country and year fixed effects. The inclusion of year fixed effects may affect the magnitude and significance of the policy coefficients, a result that will be discussed in Chapter 3.

The models estimate controlled correlations rather than causal effects, since fully resolving the problem of reverse causality would require techniques that go beyond the scope of this thesis.

The results of all the estimations described above are presented and discussed in Chapter 3, where they will be related to the three hypotheses formulated in Chapter 1.

Chapter 3 – Analysis

Based on the empirical strategy outlined in Chapter 2, this chapter presents and discusses the econometric results for OECD countries. To test the robustness of the estimates and avoid bias issues, the results for each hypothesis are presented across three progressive specifications, ranging from the model without fixed effects to the specification with only country-specific fixed effects, up to the most conservative model that simultaneously includes country and time fixed effects.

The analysis follows the logical order of the three initial hypotheses. Starting with an assessment of the impact of carbon pricing on production-based emissions, the analysis then extends to consumption-based emissions; the comparison of the estimated coefficients for these two indicators forms the core of the empirical test on the phenomenon of carbon leakage. Finally, the chapter examines how technological intensity and green innovation moderate the effectiveness of these environmental policies.

3.1 *H1* – Carbon Pricing and Production-Based Emissions

Hypothesis 1 predicts that carbon pricing instruments are associated with a significant reduction in production-based emissions. As shown in Table 3, the results broadly confirm this prediction, with differences in magnitude and robustness between the carbon tax and ETS across specifications. This section first presents the estimates using dummy variables and then examines the price specifications as a complementary robustness check.

Table 3. *Carbon Pricing and Production-Based Emissions: Dummy Variable Specifications*

	No FE	Country FE	Country + Year FE	No FE	Country FE	Country + Year FE
	Spec. 1	Spec. 2	Spec. 3	Spec. 1	Spec. 2	Spec. 3
<i>Dependent variable: $\ln(EP)$</i>	CT_d only			$CT_d + ETS_d$		
CT_d	-0.654*** (0.109)	-0.107*** (0.018)	-0.045** (0.017)	-0.387*** (0.102)	-0.089*** (0.017)	-0.027† (0.015)
ETS_d				-0.863***	-0.180***	-0.243***

				(0.102)	(0.018)	(0.022)
<i>lngdp_{pc}</i>	0.652***	0.051***	0.156***	0.814***	0.161***	0.203***
	(0.059)	(0.014)	(0.029)	(0.062)	(0.019)	(0.027)
<i>ind</i>	0.084***	0.016***	0.009**	0.072***	0.009***	0.005†
	(0.010)	(0.003)	(0.003)	(0.011)	(0.003)	(0.003)
<i>eng</i>	-0.016***	-0.006***	-0.003*	-0.016***	-0.005***	-0.002†
	(0.004)	(0.001)	(0.001)	(0.004)	(0.001)	(0.001)
Country FE	No	Yes	Yes	No	Yes	Yes
Year FE	No	No	Yes	No	No	Yes
R ²	0.162	0.991	0.993	0.221	0.993	0.994
N	1,035	1,035	1,035	1,035	1,035	1,035

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. When estimated alone in the most conservative specification (country and year fixed effects), *ETS_d* yields $\beta = -0.246^{***}$ (SE = 0.022), confirming the robustness of the result.

In Specification 1 (Spec. 1) for the carbon tax dummy variable, the coefficient of -0.654 captures an unconditional correlation between the adoption of the carbon tax and lower emissions. However, this also reflects that the countries adopting the carbon tax are structurally different from the others, as they are wealthier, more service-oriented, and already on a path of declining emissions.

In fact, when country FEs are added in Spec. 2, the coefficient drops to -0.107, representing a substantial result since it remains significant and negative after the control that identifies the within-country effect, i.e., each country compared to itself before and after adoption, eliminating the structural differences present in Spec. 1.

In Spec. 3, with both country and year FEs, the coefficient drops further to -0.045. This is attributable to the gradual and monotonically increasing adoption of the carbon tax in the sample, from 2 countries in 1995 to 19 countries in 2023, which leads to this trend being partially absorbed by the annual dummies, which capture any phenomenon common to all countries in each year. Despite this, *CT_d* continues to be significant at p=0.009 even in the most conservative specification, with an effect associated with a reduction in EP of 4.4%.

In Specification 3, when CT_d and ETS_d are jointly estimated, CT_d becomes statistically insignificant at the 5% level ($p=0.084$), indicating that, with both FE and ETS_d included in the model, the residual within-country variation in CT_d is insufficient to precisely identify its effect. Therefore, the CT_d result should be interpreted primarily based on the specification in which it was estimated alone.

The contrast between CT_d and ETS_d reveals their divergent patterns: ETS_d has a coefficient of -0.243 in the combined Spec. 3, more stable compared to prior specifications and highly significant throughout the progression. This strongly contrasts with CT_d , as the carbon tax coefficient diminishes progressively with the inclusion of FE. This phenomenon is explained by the simultaneous adoption of the EU ETS in 2005 by 23 European countries, which creates a significant temporal discontinuity that the time FEs, capturing common shocks across all 36 countries in each year, do not absorb.

Additionally, the percentage effect in Spec. 3 of -21.8% significantly exceeds that of the carbon tax, attributable to the ETS mechanism, which imposes a fixed cap on aggregate emissions in the covered sectors, while the carbon tax sets the price but leaves the quantity unregulated, producing more gradual incentives for reduction.

Simultaneously, Table 4 presents the results for the continuous price specifications, enabling an evaluation of whether the intensity of the price signal, rather than the mere presence of the instrument, drives the reduction in production-based emissions.

Table 4. *Carbon Pricing and Production-Based Emissions: Price Variable Specifications*

	No FE	Country FE	Country + Year FE	No FE	Country FE	Country + Year FE
	Spec. 1	Spec. 2	Spec. 3	Spec. 1	Spec. 2	Spec. 3
<i>Dependent variable: $\ln(EP)$</i>						
		CT_p			ETS_p	
CT_p	-0.013*** (0.002)	-0.004*** (0.000)	-0.003*** (0.000)			
ETS_p				-0.015*** (0.002)	-0.004*** (0.000)	-0.005*** (0.000)

<i>lngdp_{pc}</i>	0.662*** (0.060)	0.052*** (0.014)	0.136*** (0.029)	0.701*** (0.060)	0.107*** (0.013)	0.195*** (0.028)
<i>ind</i>	0.081*** (0.010)	0.015*** (0.003)	0.009** (0.003)	0.077*** (0.011)	0.017*** (0.002)	0.007** (0.003)
<i>eng</i>	-0.008* (0.004)	-0.005*** (0.001)	-0.002 (0.001)	-0.017*** (0.003)	-0.004*** (0.001)	-0.002† (0.001)
Country FE	No	Yes	Yes	No	Yes	Yes
Year FE	No	No	Yes	No	No	Yes
R ²	0.155	0.992	0.993	0.168	0.993	0.994
N	1,016	1,016	1,016	1,025	1,025	1,025

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. CT_p = Carbon Tax price (USD/tCO_{2e}); ETS_p = ETS price (USD/tCO_{2e}). The reduced N for CT_p (N = 1,016) and ETS_p (N = 1,025) relative to the dummy specifications (N = 1,035) reflects 29 country-years in which a carbon pricing instrument was active, but the price was not available in the source. Standard errors reported as (0.000) round to zero at three decimal places.

CT_p is significant in all three specifications, with coefficients of -0.013, -0.004, and -0.003. Notably, in Spec. 3, a 1 USD/tCO_{2e} increase in the carbon tax rate is associated with a 0.3% reduction in EP ; in perspective: while a country with a symbolic carbon tax of 10 USD/tCO_{2e} achieves only 3%, Sweden, with the highest recorded carbon tax price in the sample at approximately 169 USD/tCO_{2e}, achieves an estimated effect of about 37%.

This finding is consistent both with the Pigouvian mechanism (Pigou, 1932), stating that it is not the formal presence of the instrument but the intensity of the economic signal that determines firms' response; and with Best et al. (2020), who find that the effectiveness of the carbon tax increases with the price level.

Moreover, ETS_p shows an even larger coefficient in Spec. 3 (-0.005 per USD/tCO_{2e}), consistent with the higher dummy coefficient of ETS_d , demonstrating that the instrument is not only adopted by more countries but, at the same price, generates greater emission reductions for the cap mechanism.

Furthermore, the findings from the control variables are all consistent with theoretical expectations: $lngdp_{pc}$ is positive and confirms the relationship between economic growth and emissions; a positive ind reflects the higher carbon intensity of industrialized

economies; and the negative *eng* demonstrates that the energy transition reduces emissions regardless of carbon pricing.

In conclusion, the results show that both instruments substantially and robustly reduce *EP*, with different magnitudes and stability patterns that reflect structural differences in their operating mechanisms. The remaining question is whether this reduction in territorial emissions translates into an equivalent reduction in consumption-based emissions, and this is precisely what the next section addresses.

3.2 H2 – Carbon Leakage and Consumption-Based Emissions

After establishing that carbon pricing significantly reduces *EP*, the analysis now turns to consumption-based emissions to test whether the reductions documented in Section 3.1 translate into equivalent decreases in actual carbon footprint or whether part of the effect is mitigated by carbon leakage through international trade.

As shown in Tables 5 and 6, the results broadly support *H2*: the effects on *EC* are significant but systematically smaller than those on production-based emissions, with price specifications showing the most evident gap.

Table 5. *Carbon Pricing and Consumption-Based Emissions: Dummy Variable Specifications*

	No FE	Country FE	Country + Year FE	No FE	Country FE	Country + Year FE
	Spec. 1	Spec. 2	Spec. 3	Spec. 1	Spec. 2	Spec. 3
<i>Dependent variable: ln(EC)</i>	<i>CT_d only</i>			<i>CT_d + ETS_d</i>		
<i>CT_d</i>	−0.579*** (0.103)	−0.100*** (0.019)	−0.041* (0.018)	−0.330** (0.097)	−0.084*** (0.018)	−0.025 (0.017)
<i>ETS_d</i>				−0.802*** (0.098)	−0.159*** (0.019)	−0.219*** (0.022)
<i>lngdp_{pc}</i>	0.670***	0.146***	0.229***	0.821***	0.243***	0.272***

	(0.055)	(0.015)	(0.029)	(0.058)	(0.020)	(0.027)
<i>ind</i>	0.078***	0.012***	0.004	0.067***	0.006*	0.000
	(0.010)	(0.003)	(0.003)	(0.010)	(0.003)	(0.003)
<i>eng</i>	-0.008*	-0.004**	-0.001	-0.008*	-0.004*	-0.001
	(0.003)	(0.002)	(0.001)	(0.003)	(0.001)	(0.001)
Country FE	No	Yes	Yes	No	Yes	Yes
Year FE	No	No	Yes	No	No	Yes
R ²	0.156	0.989	0.991	0.212	0.990	0.992
N	1,035	1,035	1,035	1,035	1,035	1,035

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. When estimated alone in the most conservative specification (country and year fixed effects), ETS_d yields $\beta = -0.221^{***}$ (SE = 0.022), confirming the robustness of the result.

Initially, in Spec. 1, CT_d yields a coefficient of -0.579, gradually decreasing to -0.100 in Spec. 2 and reaching -0.041 in Spec. 3, which is significant at $p=0.025$ with an associated percentage effect of -4.0%. CT_d , therefore, replicates in EC the same pattern observed in EP for the same reasons as the latter, but with a more pronounced effect when CT_d is estimated with ETS_d in Spec. 3, since, compared to the partially significant $p=0.084$ in EP , the coefficient in this case becomes completely insignificant, -0.025 with $p=0.146$, reflecting how consumption-based emissions are more sensitive to global trade trends that are absorbed by the time FE.

ETS_d , as in EP , remains highly significant across all specifications, with the coefficient shifting from -0.802 in Spec. 1 to -0.159 in Spec. 2 to -0.219 in Spec. 3, corresponding to a percentage effect of -19.9%, and where the stability between the last two specifications is again attributable to the discontinuity of the EU ETS adoption in 2005, which the time FE do not absorb.

Turning to the price variables, Table 6 presents the results for CT_p and ETS_p on EC in the three specifications.

Table 6. *Carbon Pricing and Consumption-Based Emissions: Price Variable Specifications*

	No FE	Country FE	Country + Year FE	No FE	Country FE	Country + Year FE
	Spec. 1	Spec. 2	Spec. 3	Spec. 1	Spec. 2	Spec. 3
<i>Dependent variable: $\ln(EC)$</i>		CT_p			ETS_p	
CT_p	-0.011*** (0.001)	-0.002*** (0.000)	-0.001** (0.000)			
ETS_p				-0.013*** (0.002)	-0.003*** (0.000)	-0.004*** (0.000)
$\ln gdp_{pc}$	0.681*** (0.056)	0.141*** (0.015)	0.226*** (0.029)	0.710*** (0.056)	0.180*** (0.015)	0.260*** (0.028)
ind	0.076*** (0.010)	0.012*** (0.003)	0.004 (0.003)	0.071*** (0.010)	0.014*** (0.003)	0.002 (0.003)
eng	-0.001 (0.004)	-0.004** (0.002)	-0.001 (0.001)	-0.009** (0.003)	-0.003* (0.001)	-0.001 (0.001)
Country FE	No	Yes	Yes	No	Yes	Yes
Year FE	No	No	Yes	No	No	Yes
R ²	0.148	0.989	0.991	0.160	0.990	0.992
N	1,016	1,016	1,016	1,025	1,025	1,025

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. CT_p = Carbon Tax price (USD/tCO₂e); ETS_p = ETS price (USD/tCO₂e). The reduced N for CT_p (N = 1,016) and ETS_p (N = 1,025) reflects 29 country-years in which a carbon pricing instrument was active, but the price was not available in the source. Standard errors reported as (0.000) round to zero at three decimal places.

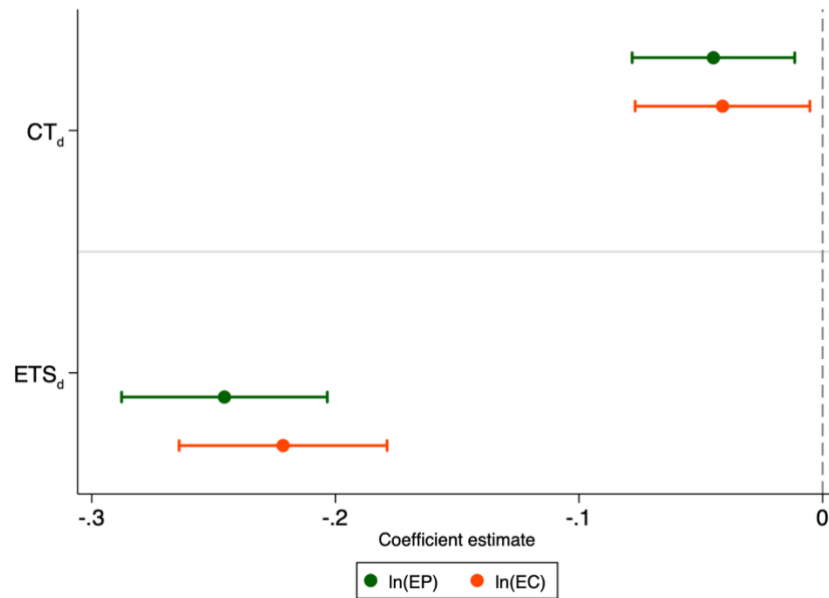
The price coefficients confirm the pattern observed with the dummy variables, namely the significance of CT_p across all specifications (-0.011***, -0.002***, -0.001**) and of ETS_p similarly (-0.013***, -0.003***, -0.004***), although with lower values than in the corresponding *EP* specifications. The coefficient of ETS_p in Spec. 3, as noted in Chapter 2,

should be interpreted with caution due to limited variation in the pre-2005 period, when the ETS was absent for all countries in the sample.

Finally, a consistent pattern emerges from a direct comparison of the estimated coefficients across both dependent variables in Spec. 3.

The effect of carbon pricing on consumption-based emissions is statistically significant, with confidence intervals excluding zero in all four cases, but consistently smaller than that on production-based emissions, as illustrated in Figure 3.

Figure 3. Carbon Pricing Effects on Production-Based and Consumption-Based Emissions: Dummy Variable Specifications, Specification 3



Note. Dots represent coefficient estimates from Specification 3 (country and year fixed effects), with CT_d and ETS_d estimated separately. Horizontal bars represent 95% confidence intervals based on robust standard errors. Percentage effects are computed as $(e^{\beta} - 1) \times 100$: CT_d on EP = -4.4%, CT_d on EC = -4.0%; ETS_d on EP = -21.8%, ETS_d on EC = -19.9%.

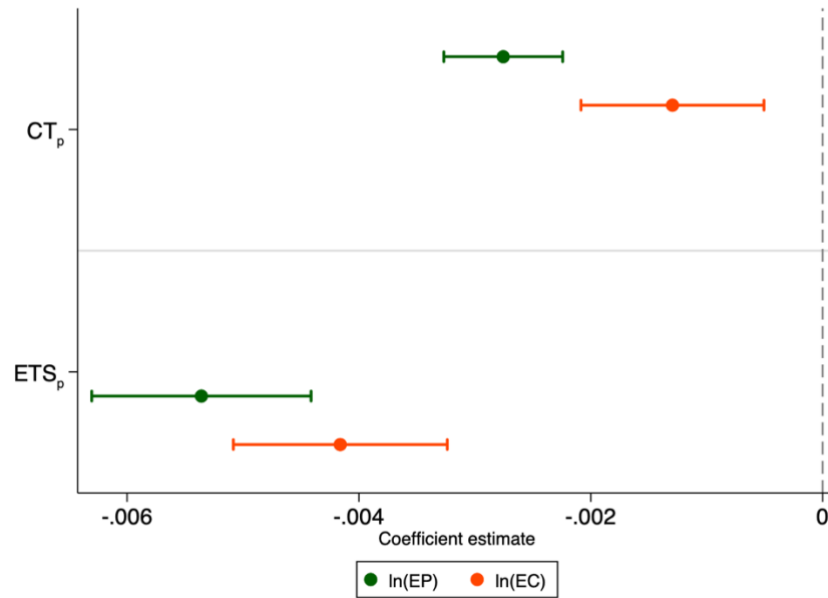
CT_d has coefficients of -0.045** on EP and -0.041* on EC , while ETS_d yields -0.246*** on EP and -0.221*** on EC . Indeed, CT_d , with a reduction of 4.4% for EP and 4.0% for EC , has a difference of 0.4 percentage points; while the respective reductions of 21.8% and 19.9% by ETS_d make the difference even wider at 1.9 percentage points, representing the first indication that the carbon tax effect diminishes when the entire value chain is considered, including emissions embedded in imports.

Statistical significance accounts for the main difference, since, as reported in Table 5, when CT_d and ETS_d are included in the same model, CT_d remains marginally significant on EP

($p=0.084$) but loses all significance on EC ($p=0.146$). This indicates that, net of all controls, the carbon tax drives part of the reduction in EP but is insufficient to identify a robust effect on actual emissions.

The gap between EP and EC becomes more visible when prices are also considered, as shown in Figure 4.

Figure 4. Carbon Pricing Effects on Production-Based and Consumption-Based Emissions: Price Variable Specifications, Specification 3



Note. Dots represent coefficient estimates from Specification 3 (country and year fixed effects), with CT_p and ETS_p estimated separately. Horizontal bars represent 95% confidence intervals based on robust standard errors. CT_p = Carbon Tax price (USD/tCO_{2e}); ETS_p = ETS price (USD/tCO_{2e}). Coefficients represent the percentage change in emissions associated with a 1 USD/tCO_{2e} increase in the respective price.

In terms of price variables, the comparison of CT_p between EP and EC in Spec. 3 is the most telling result of the entire $H2$ analysis: a 1 USD/tCO_{2e} increase in the carbon tax price reduces territorial emissions by 0.3% but only by 0.1% for consumption emissions. This difference measures carbon leakage: the portion of domestic emission reductions that does not translate into a decrease in the overall carbon footprint, since carbon-intensive production shifts to unregulated countries and re-enters as emissions embedded in imports.

For ETS_p , the difference is smaller, since a 1 USD/tCO_{2e} increase reduces EP by 0.5% and EC by 0.4%; this demonstrates that, as previously noted, the cap mechanism is less susceptible to leakage.

The analysis shows that carbon leakage is real but partial and that the hypothesis *H2*, which predicted a weaker effect on *EC* (confirmed by the results) or a null effect (not confirmed), is partially supported: *EC* continues to decrease with the introduction of carbon pricing, but to a lower extent than *EP*. This result is consistent with the empirical literature: Schroeder & Stracca (2025) document how carbon taxes reduce domestic emissions but increase imports of carbon-intensive goods; Teusch et al. (2024) find weaker effects on consumption-based emissions in sectors at high risk of leakage.

Two factors explain why leakage is not total, and why *EC* continues to decline rather than remain stable: firstly, OECD countries trade primarily with each other, limiting the transfer of emissions to unregulated economies; secondly, part of the effect of carbon pricing also acts on the final demand side and not just on production.

This gap between *EP* and *EC* forms the basis for border adjustment mechanisms such as the CBAM, which imposes a cost on emissions embedded in imports entering the EU (European Parliament & Council of the European Union, 2023).

3.3 *H3* – The Moderating Role of Green Innovation

The purpose of this section is to test Hypothesis 3, which is whether carbon pricing is more effective in countries with higher levels of green innovation, using three stages: first, testing whether carbon pricing stimulates innovation; second, checking whether innovation moderates the effect on emissions using dummy variables; and finally, verifying whether this is confirmed with prices.

Starting with the first exploratory block, which tests whether CT_d and ETS_d affect the *GreenPat* variable. Even in this case, the model extends to the three specifications used previously (without FE, with country FE, and with country and year FE), as shown in Table 7.

Table 7. *Carbon Pricing and Green Innovation: Green Patent as Dependent Variable*

	No FE	Country FE	Country + Year FE
<i>Dependent variable: ln(GreenPat)</i>	Spec. 1	Spec. 2	Spec. 3
CT_d	-0.016	0.111*	0.094†

	(0.064)	(0.053)	(0.052)
<i>ETS_d</i>	-0.298***	0.051	-0.205***
	(0.058)	(0.058)	(0.063)
<i>lngdp_{pc}</i>	2.023***	1.021***	0.532***
	(0.052)	(0.078)	(0.106)
<i>ind</i>	0.030***	-0.032***	0.012
	(0.008)	(0.009)	(0.009)
<i>eng</i>	0.009***	-0.005	-0.004
	(0.002)	(0.005)	(0.005)
Country FE	No	Yes	Yes
Year FE	No	No	Yes
R ²	0.762	0.933	0.949
N	1,014	1,014	1,014

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. Dependent variable is $\ln(\text{GreenPat}_{it})$ = natural log of Green Patents per million inhabitants.

The Carbon Tax Dummy variable has an insignificant effect ($p=0.804$), apparently indicating no raw correlation between carbon tax and patents. However, with country fixed effects (FE), this effect becomes significant and positive (0.111^* , $p=0.036$), showing that, within a country, Green Patents increase following the adoption of a carbon tax; the same trend holds when using both FEs, with the coefficient remaining positive ($0.094^\dagger$, $p=0.072$).

This is consistent with the Porter Hypothesis (Porter & van der Linde, 1995), which argues that well-designed market-based environmental regulations create incentives for innovation, and with Lim & Prakash (2023), who state that carbon pricing policies are associated with a significant increase in climate mitigation patent applications.

For the ETS dummy variable, the pattern is opposite and more complex: without FE, the coefficient is negative (-0.298^{***}); with country FE, it becomes insignificant (0.051); and finally, with both FE, it returns to being negative and significant (-0.205^{***}). This counterintuitive result from Spec. 3 represents a relative deceleration, not an absolute reduction: within countries that have adopted the ETS, Green Patents growth has been slower

than the global trend captured by the time FE. A plausible channel of interpretation is a lagged innovation mechanism, as noted by Lim & Prakash (2023), i.e., the innovation process takes time to translate into patent applications, and therefore a contemporary specification cannot fully capture the medium-term innovation response to ETS adoption. This interpretation is consistent with Chen et al. (2025), whose systematic review identifies the policy lack of stringency and regulatory uncertainty as the primary factors limiting innovation incentives in the ETS, especially in the early stages of the EU ETS, characterized by near-zero carbon prices due to permit over-allocation.

Overall, the results from Stage 1 suggest that the relationship between carbon taxes and innovation is instrument-specific and potentially subject to temporary dynamics.

In Stage 2, illustrated in Table 8, the perspective is reversed by testing whether green innovation amplifies the effect of carbon pricing on emissions. To this end, Specifications 2a and 2b, described in Table 8, introduce an interaction term between carbon pricing dummy variables and $\ln(\text{GreenPat})$, allowing the effects of CT_d and ETS_d on EP and EC , respectively, to vary with the level of green innovation across countries.

Table 8. *The Moderating Role of Green Innovation: Interaction Model with Dummy Variable Specifications*

	$\ln(EP)$	$\ln(EC)$
<i>Dependent variable: $\ln(EP)$ and $\ln(EC)$</i>	Spec. 2a	Spec. 2b
CT_d	0.112*** (0.022)	0.082** (0.025)
ETS_d	-0.273*** (0.030)	-0.311*** (0.036)
$CT_d \times \ln(\text{GreenPat})$	-0.070*** (0.008)	-0.053*** (0.008)
$ETS_d \times \ln(\text{GreenPat})$	0.033*** (0.008)	0.055*** (0.010)
$\ln(\text{GreenPat})$	0.052*** (0.012)	0.030* (0.013)

$lngdp_{pc}$	0.193*** (0.031)	0.293*** (0.035)
ind	0.007** (0.003)	0.002 (0.003)
eng	-0.004*** (0.001)	-0.003* (0.001)
Country FE	Yes	Yes
Year FE	Yes	Yes
R ²	0.995	0.993
N	1,014	1,014

Note. Robust standard errors in parentheses. †p < .10, *p < .05, **p < .01, ***p < .001. All specifications include country and year fixed effects. The marginal effect of CT_d on $\ln(EP)$ at the sample mean of $\ln(GreenPat) = 1.79$ is $0.112 - 0.070 \times 1.79 = -0.013$, corresponding to a reduction of 1.3%. The marginal effect of ETS_d on $\ln(EP)$ at the sample mean is $-0.273 + 0.033 \times 1.79 = -0.214$, corresponding to -19.3%.

The main coefficient for CT_d is positive, 0.112*** for EP and 0.082** for EC , but this represents the baseline effect in the absence of green innovation, a condition that does not hold in the sample, where all countries exhibit positive levels of *GreenPat*.

The actual effect depends on the interaction; in fact, the interaction term is negative and highly significant for both EP and EC , meaning that as green innovation increases, the carbon tax becomes progressively more effective in reducing emissions. This occurs for all countries with $\ln(GreenPat) > 0.112/0.070 = 1.60$ on EP , and $\ln(GreenPat) > 0.082/0.053 = 1.55$ on EC , corresponding to more than $e^{1.6} \approx 5$ green patents per million inhabitants, a threshold met by almost all OECD countries.

At the sample's average value ($\ln(GreenPat) \approx 1.79$), the net effect is equal to $0.112 - 0.070 \times 1.79 = -0.013$, corresponding to a -1.3% reduction in EP . For EC , the mechanism is analogous, $0.082 - 0.053 \times 1.79 = -0.013$, which is also -1.3%.

The ETS_d has a highly significant and strongly negative main coefficient for both dependent variables, indicating the robust emission-reducing effect of ETS. However, the interaction term $ETS_d \times \ln(GreenPat)$ is positive and significant, whereas $H3$ predicted a negative

sign; this suggests that in countries with higher levels of green innovation, the effect of ETS on emissions is less pronounced.

At the mean value ($\ln(\text{GreenPat}) = 1.79$), the effect on EP is equal to $-0.273 + 0.033 \times 1.79 = -0.214$, i.e., a 19.3% reduction, and $-0.311 + 0.055 \times 1.79 = -0.213$ on EC , corresponding to -19.1% .

Therefore, the ETS substantially reduces emissions, but the direction of the interaction is opposite to what is expected. This result suggests that, unlike the carbon tax, which operates continuously on the price margin, the ETS operates with a fixed cap on aggregate quantities and therefore, in countries with high green innovation, emissions had already been partially reduced through technological progress independently of the ETS, so the cap is less binding because the additional reduction margin attributable to the ETS has already been exhausted. Thus, CT_d and innovation act as complements, while ETS_d and innovation act as partial substitutes.

Finally, $\ln(\text{GreenPat})$ has a direct, positive, and significant effect on EP (0.052***) and on EC (0.030*), reflecting that periods of higher patenting activity tend to coincide with periods of higher economic activity.

Conclusively, $H3$ yields a partial result for Stage 2: the hypothesis is confirmed for CT_d in both EP and EC but not confirmed for ETS_d . Perhaps the most significant finding is that green innovation significantly amplifies the effect of the carbon tax, and that this extends to consumption-based emissions, suggesting that in highly innovative countries, carbon pricing reduces not only what is produced domestically but also what is ultimately consumed.

To ensure consistency with $H1$ and $H2$, the version with prices, CT_p and ETS_p , is also estimated in Spec. 2c and Spec. 2d to determine whether the price level interacts with green innovation to produce greater emission reductions, as shown in Table 9.

Table 9. *The Moderating Role of Green Innovation: Interaction Model with Price Variable Specifications*

	$\ln(EP)$	$\ln(EC)$
<i>Dependent variable: $\ln(EP)$ and $\ln(EC)$</i>	Spec. 2c	Spec. 2d
CT_p	0.004**	0.000

	(0.001)	(0.002)
ETS_p	−0.006***	−0.005***
	(0.001)	(0.001)
$CT_p \times \ln(\text{GreenPat})$	−0.002***	0.000
	(0.000)	(0.000)
$ETS_p \times \ln(\text{GreenPat})$	0.000*	0.001***
	(0.000)	(0.000)
$\ln(\text{GreenPat})$	0.044***	0.032*
	(0.013)	(0.015)
$\ln gdp_{pc}$	0.198***	0.290***
	(0.031)	(0.034)
ind	0.006*	0.001
	(0.003)	(0.003)
eng	−0.004***	−0.003*
	(0.001)	(0.001)
Country FE	Yes	Yes
Year FE	Yes	Yes
R ²	0.995	0.992
N	986	986

Note. Robust standard errors in parentheses. * $p < .05$, ** $p < .01$, *** $p < .001$. All specifications include country and year fixed effects. CT_p = Carbon Tax price (USD/tCO₂e); ETS_p = ETS price (USD/tCO₂e). Standard errors reported as (0.000) round to zero at three decimal places. N = 986 reflects 29 country-years in which a carbon pricing instrument was active but the price was not available in the source.

CT_p 's main coefficient on EP is positive (0.004**), indicating that in countries with low green innovation, higher carbon tax rates are associated with higher domestic emissions. This occurs because, in countries with lower levels of innovation, high carbon tax rates increase production costs without firms having the technologies to respond by reducing emissions.

However, the interaction term $CT_p \times \ln(\text{GreenPat})$ is negative and highly significant (-0.002***), with the threshold beyond which an increase in the carbon tax price produces a net reduction in EP set at $\ln(\text{GreenPat}) > 0.0036476/0.0015447 = 2.36$. The fact that this threshold is higher than that of the dummy variables (1.60) means that the price requires a higher level of pre-existing innovation to translate into reductions in EP .

On EC , instead, neither CT_p nor $CT_p \times \ln(\text{GreenPat})$ are significant ($p=0.806$ and $p=0.827$), meaning that carbon tax levels do not reduce consumption-based emissions, even in the most innovative countries. This important result is consistent with the leakage mechanism discussed in $H2$, namely that the carbon tax affects domestic production costs but not the composition of imports.

Furthermore, the results from Spec. 2d confirm those from Spec. 2a and Spec. 2b, i.e., that ETS robustly and highly significantly reduces both EP and EC . The interaction term is positive for both dependent variables, confirming the partial substitution by ETS already observed with the dummy variables. The threshold beyond which ETS_p ceases to reduce EP is $\ln(\text{GreenPat}) > 0.0055149/0.0003551 \approx 15.5$, an unattainable value that demonstrates how the ETS always reduces EP regardless of the level of innovation, but with decreasing intensity as the latter increases.

Therefore, the specifications with prices confirm the pattern of the dummies, except that for the carbon tax, the price signal is insufficient to reduce EC even in innovative countries; thus, only the adoption of the instrument (CT_d), which captures the institutional effect in the long run, produces significant reductions in EC in interaction with innovation. For ETS, instead, the results with prices are fully consistent with those of the dummy variables.

Conclusion

Testing whether carbon pricing truly reduces global emissions or merely shifts the problem elsewhere was the question that sparked this thesis. In this regard, the three hypotheses agree on the effectiveness of carbon pricing; however, its mechanism and impact depend on the specific policy instrument and the country's technological context.

Starting with Hypothesis *H1*, the results confirmed that both carbon taxes and ETS significantly reduce domestic emissions, with the ETS showing a more significant absolute effect in price-based specifications.

Furthermore, Hypothesis *H2* demonstrated that the reduction also extends to consumption-based emissions; indeed, *EC* decreases to a lesser extent than *EP*, and it is precisely this gap that serves as a measure of leakage. For the carbon tax, in particular, less than half of the effect on prices is transferred to consumption-based emissions. Therefore, this hypothesis is partially confirmed, as the effect is weaker than predicted for both instruments, but insignificant only for the carbon tax in the combined model.

Finally, Hypothesis *H3* introduced the dimension of heterogeneity, demonstrating that the effect of carbon pricing varies across countries and depends on their level of technological endowment: green innovation acts as an amplifier of the carbon tax, meaning that its effectiveness increases with a country's level of green patents; but the same is not true for the ETS, where pre-existing innovation slightly reduces the marginal effectiveness of the cap.

Together, these findings suggest that governments, basing their estimation solely on domestic emissions, tend to overestimate the effectiveness of carbon pricing, which varies across policy instruments: an ETS, compared to a national carbon tax, is more effective in reducing global emissions because the supranational mechanism eliminates cost asymmetries among producers.

The CBAM is a notable institutional response to the problem; however, it is incomplete because, as explained in Chapter 1, it applies only to imports and not to exports.

It is precisely at this historic moment, as the CBAM has recently become fully operational, carbon prices in Europe have reached historically significant levels, and political pressure to extend ETS systems to other sectors is growing, that the framework established by this study,

namely the measurement of the effectiveness of carbon pricing on both *EP* and *EC* dimensions, will become increasingly necessary.

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