CARBON PRICING, BORDER ADJUSTMENT AND RENEWABLE ENERGY INVESTMENT: A NETWORK APPROACH

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Abstract

An increase of €100 per tonne in the EU carbon price reduces the carbon footprint but lowers GDP due to higher energy costs and carbon leakage. Using a dynamic multi-sector, multi-country model augmented with an energy block that includes endogenous renewable energy investment, we analyze the macroeconomic and emissions effects of a carbon price. Investment in renewable energy mitigates electricity price increases in the medium term, leading to a smaller GDP loss (up to −0.4%) and a larger emissions reduction (24%) in the EU. Neglecting renewable energy investment overestimates the negative economic impact. We also find that a Carbon Border Adjustment Mechanism (CBAM) reduces carbon leakage but slightly hurts GDP and inflation as the competitive gain is offset by the higher costs of imported intermediate inputs.

Keywords: carbon pricing, renewable energy investment, carbon border adjustment, production networks.

JEL classification: C6, H2, Q5.

Resumen

Un incremento de 100 euros por tonelada en el precio del CO_2 en la Unión Europea (UE) reduce la huella de carbono, pero disminuye el PIB debido al aumento de los costes energéticos y a la deslocalización de la producción. A partir de un modelo dinámico multisectorial y multipaís, extendido con un módulo energético que incluye inversión endógena en energía renovable, analizamos los efectos macroeconómicos y ambientales derivados del incremento del precio del CO_2. La inversión en energía renovable mitiga el aumento de los precios de la electricidad a medio plazo, lo que conduce a una menor caída del PIB (del –0,4 %) y a una mayor reducción de las emisiones (24 %) en la UE. Ignorar el canal de inversión en energía renovable sobreestima sustancialmente el impacto adverso en la actividad económica. También encontramos que el Mecanismo de Ajuste en Frontera por Carbono (CBAM, por sus siglas en inglés) reduce la fuga de carbono, aunque con resultados marginalmente negativos en términos de PIB e inflación, ya que la ganancia de competitividad se compensa con el aumento del coste de los insumos intermedios importados.

Palabras clave: precios del CO_2, inversión en energía renovable, ajuste en frontera por carbono, redes de producción.

Códigos JEL: C6, H2, Q5.

1 Introduction

In this paper, we examine the macroeconomic and environmental implications of carbon pricing and carbon border adjustment by constructing a network model with a detailed representation of the energy sector.

Our contribution to the existing literature lies in developing a dynamic, multi-sector, multi-country model enhanced with an energy block. This block captures the interplay between fossil fuels and electricity, which can be generated from both fossil and renewable sources. Notably, the model features endogenous investment in renewable energy and integrates a merit-based electricity pricing system, providing a more realistic representation of the energy transition. Using this framework, we evaluate the impacts of an increase in the effective carbon price within the EU and the introduction of a CBAM.

We find that an increase in the EU's effective carbon price negatively impacts GDP levels in the medium term and permanently elevates price levels in this region. However, our analysis reveals that models neglecting the renewable energy investment implied by these mechanisms significantly overestimate the adverse impact on economic activity by a factor of two. The higher fossil-based energy costs, due to carbon pricing, provides an opportunity for green electricity production and stimulates short-term investment demand. The subsequent growth in green electricity production mitigates the increase in the cost of the energy mix in the medium term.

Our model presents an enriched approach to the energy sector by differentiating between various fossil fuel sources (coal, natural gas, and oil) and electricity. Moreover, within the electricity sector, we distinguish between producers of fossil-based and renewable electricity under a merit-based pricing system. We calibrate different substitution elasticities between energy sources as well as the price captured by renewable electricity producers with respect to the cost of fossil fuels. This specification allows us to calculate two energy adjustment margins, both the electrification process and the increase in the weight of renewables in the electricity mix. These two channels are indistinguishable in models with a generic green and polluting sector. The increase in the carbon prices raises the price received by renewable electricity producers, which incentivizes more green generation capacity until the cannibalization of prices received by the latter resets the new equilibrium. This framework allows us to capture a greater diversity of sectoral effects, providing a more nuanced understanding of the transitions not only within the energy sectors, but also across sectors and countries.

Additionally, we also include in the model a border adjustment mechanism, a tariff on EU imports based on their embedded carbon content. This policy aims to curb carbon leakage through import substitution, which increases the costs of European producers and reduces their competitiveness. We show that the introduction of a CBAM contributes to reducing carbon leakage, but comes at an additional cost in terms of GDP. The reason is that the border adjustment makes energy-intensive sectors with an upstream position as key input suppliers for the other sectors of the economy, such as chemicals or metallurgy, more expensive. Consequently, the CBAM's protectionist effect for some sectors results in an aggregate economic loss. This outcome is overlooked by models that disregard the complex structure of global value chains. Moreover, we show that ignoring the endogenous response of renewable energy overestimates the CO_2 reduction benefits of CBAM.

Our model allows us to analyse the decomposition of CO_2 emission reductions resulting from environmental policies. This decomposition allows us to separate the percentage of emissions saved by a decrease in production, by a sectoral reallocation of production, by a change in the mix of intermediate inputs, by energy savings, or by an increase in renewables within electricity production.

In our central scenario, the increase in the carbon price by €100 per tonne of CO_2 and CBAM reduces the level of EU GDP by 0.6% in the medium term and increases the price level by 1.3%. The reduction in emissions is close to 25%. If the role of renewables is ignored, the cost increases to 2.6% of GDP with an emission reduction of only 8%. The dynamics of the transition depend on the degree of phasing-in of the carbon price.

The rest of the paper is organised as follows. In Section 2, we summarise the literature on the role of carbon pricing mitigating the climate change, how it encourages the development of renewable energy and how carbon leakage could be tackled. Section 3 explains how the model is built and its main properties. The calibration of the model and data sources employed are explained in Section 4. In Section 5, we present the results and, finally, Section 6 draws the main conclusions.

2 Background

Carbon pricing, by increasing the cost of goods and services according to their carbon footprint, is a powerful and efficient way of reducing emissions since it gives economic agents an incentive to find ways to conserve energy and switch to greener sources (Timilsina, 2022; Blanchard et al., 2023). Carbon pricing is also effective in promoting innovation since it encourages the adoption of low-carbon technologies and energy sources, and foster the research and development in cleaner technologies (Acemoglu et al., 2012; Aghion et al., 2016; Grubb et al., 2018; Shapiro and Walker, 2018; Timilsina, 2022).[1]

In this regard, carbon pricing incentivizes the deployment of renewable energy by increasing the competitiveness of clean energy sources relative to fossil fuels (Acemoglu et al., 2012). The development of the renewable energy sector has been frequently examined in studies using Integrated Assessment Models (e.g., Hassler et al. (2021, 2022)). We built on previous analysis and deepen the understanding of the energy transition by including in our model more detailed behavioural foundations and more comprehensive representations of economic relationships with alternative elasticity of substitution during the transition process. Recent more micro-founded models have also addressed this effect. By building a New Keynesian model for a small open economy, Airaudo et al. (2023) study how raising energy prices crowd out dirty energy use in favor of the renewable energy sector and their macroeconomic consequences. Other recent studies have evaluated the macroeconomic effects of carbon pricing incorporating both green and dirty energy sectors into their CGE or DSGE modeling approaches (Varga et al., 2022; IMF, 2022; Coenen et al., 2024; Nakov and Thomas, 2023; Olovsson and Vestin, 2023). However, these studies have not fully considered that carbon pricing not only facilitates the electrification of the economy but also supports the greening of electricity production. Specifically, they tend to neglect the interplay between polluting-based and green electricity since they do not consider the merit-based electricity pricing systems. Consequently, how the emergence of the renewable energy sector, driven by carbon pricing, impacts economic and environmental outcomes —particularly through electricity generation and pricing— remains insufficiently explored.

In addition, the absence of international coordination, local or regional carbon pricing initiatives induce carbon leakage, i.e. the displacement of activity and emissions due to the economic burden of climate policies. Carbon leakage proceeds from two main channels: the direct or competitiveness channel and the indirect channel through the global fossil fuel markets.[2] One way to mitigate

[1] Fiscal tools, along with regulatory policies, are the main instruments to encourage economic agents to reduce CO_2 emissions. At least two market failures linked to climate change could be addressed with fiscal instruments: the externalities related to emissions and those related to knowledge spillovers from research and development that may prevent their full social benefit from being harnessed. Fiscal policy tools aimed at internalizing the externality through price signals could optimally address these market failures. These tools may take the form of Pigouvian taxes on emissions or of subsidies on research or clean energy (Pigou, 1932; Stern, 2007; Farid et al., 2016; De Mooij et al., 2012; Parry et al., 2015).

[2] The 'competitiveness' channel goes through the increased cost of highly emitting industries in countries or regions imposing carbon pricing: these regions may import more 'dirty' goods and export less, resulting in an increase in emissions in non-abating regions that will compensate partially the cut of emissions obtained in the ambitious regions. Second, regions implementing carbon reduction measures demand less emissions-intensive inputs, which may become cheaper on the global market, fostering their usage in those areas with less-stringent policies, which is deemed as the 'fossil fuel market' channel.

carbon leakage is through a carbon border adjustment, i.e. imposing tariffs on imports according to their carbon content, to level the playing field with domestic production, and/or exempting exports from the carbon prices.

The literature on assessing the effects of different carbon pricing strategies on carbon leakage can be divided into two main strands. The first one relies on econometric models that use observed data from those carbon policies already implemented. The second one aims at assessing ex-ante the effects of alternative carbon policies and it is based on simulations with models, calibrated with empirical data. The former category typically finds limited or no carbon leakage when evaluating existing carbon pricing schemes (Copeland et al., 2022), which could be related to the historical lack of stringency of carbon pricing initiatives in terms of emissions covered and low effective carbon price in place. The latter approach tends to find larger leakage, especially in emissions-intensive and trade-exposed industries. Our work falls in the second group of studies and relies on multi-sector, multi-country general equilibrium model. In-depth literature reviews on the ex ante effects of carbon pricing strategies on carbon leakage, such as Böhringer et al. (2022), Felbermayr et al. (2020), Zachmann and McWilliams (2020), and Yu et al. (2021), find that the amount of carbon leakage depends on several factors, such as the stringency of carbon pricing, the geographical scope of the analysis or the magnitude of trade and fossil fuel supply elasticities. Model simulations reveal that the fossil fuel market channel tends to dominate the competitiveness one, with the exception of a situation of highly inelastic global supply of fossil fuels. This is the case because the competitiveness channel mostly affects energy-intensive and trade-exposed industries, see also Grubb et al. (2022) and Carbone and Rivers (2017), whereas leakage through the fossil fuel channel would occur even if only fossil fuels are traded.

Some studies have also explored the effects of carbon border adjustment to mitigate leakages by introducing source-specific import tariffs and export rebates. A systematic literature review (see Clausing and Wolfram (2023), Böhringer et al. (2022); Felbermayr et al. (2020); Zachmann and McWilliams (2020)) shows that it is generally found effective in reducing carbon leakage. Factors such as the sectoral coverage of the adjustment, the choice of reference emissions, the perimeter of the coalition adopting border adjustment, and the trade elasticities determine the effects of the border adjustment. Branger and Quirion (2014) and Böhringer et al. (2012) find that border adjustment can reduce leakage rates also in emissions-intensive and trade-exposed sectors. Bellora and Fontagné (2023) show that EU border adjustment could be effective in reducing carbon leakage, but competitiveness losses are expected for exporters of high-emitting industries. Coster et al. (2024) also find that the EU border adjustment reduces leakage but negatively affects household welfare as the rise in prices outweighs the benefits of lower emissions. On the contrary, other works see little gain from border adjustment (see Zachmann and McWilliams (2020), Devarajan et al. (2022)). Ernst et al. (2023) find that the overall reduction in leakage is small, but it can benefit 'dirty' domestic sectors because the cost of imports increases disproportionately, leading to a shift in demand towards domestically produced goods. In this regard, Weitzel et al. (2012) note that carbon adjustment could be used strategically without clear environmental intentions when 'dirty' domestic sectors are cleaner than those abroad. On the other hand, several other studies, such as Böhringer et al. (2015), and Branger and Quirion (2014), have concluded that while export rebates may reduce carbon leakage, import tariffs are the only measures that result in a significant overall reduction of emissions because they also decrease consumption.[3]

In this work we analyze the environmental and macroeconomic consequences of an effective carbon price increase in the EU as well as the introduction of a border tax. To conduct our analysis, we use a dynamic multi-sector, multi-country model augmented with an energy block that realistically captures endogenous investment in renewable energy. This is an open economy production and investment network model following Baqaee and Farhi (2020). A somewhat similar approach to the one conducted in this paper is the one of Ernst et al. (2023) who employ an environmental multi-sector dynamic general equilibrium model to assess the environmental and economic consequences of various designs of the carbon pricing mechanism and the carbon border adjustment, without incorporating the role of renewables investment. As in our work, the model takes into account environmental externalities and accounts for production linkages through intermediate inputs. Different from us, neither they explicitly model the role of the energy sector, especially the endogenous investment in renewables, nor consider a more detailed country and sector linkages.

In our analysis, unlike Ernst et al. (2023), the medium term positive effects on GDP come from the adaptation of sectors through new investments and market incentives for renewable energies and not from the reduction of physical risks whose incidence on activity would be clearer in longer horizons. To this end, given the importance of energy consumption in the effects of the carbon pricing, our analysis account for the endogenous development of renewable energies derived from the increasing costs of (polluting) energy inputs. Also, the level of detail of the production networks enables us to analyze the sectors most affected by the carbon pricing and by the border adjustment and with the highest carbon leakage. These are relatively upstream (at the top of the value chains), so that the effect on GDP of the border adjustment may add GDP losses in the short term. With this framework, we are able to assess the consequences of these policies from a global perspective,

[3]Note that omitting export rebates from the carbon adjustment scheme may reduce its effectiveness, as rebates can prevent leakage from losing market share abroad for emissions-intensive and trade-exposed industries. However, for countries that are large net importers of carbon intensive good and services, most of the leakage mitigation comes from import demand adjustment.

providing the determinants of the changes in GHGs emissions and the economic impact in the EU countries and in their trading partners. Finally, our model introduces endogenous energy transition, where gradual investment is taking place. Some previous studies have included this transition but in a different form. For instance, O'Ryan et al. (2020) analyse the impact of four alternative energy mix scenarios for Chile for 2030, to capture the structural change in the energy sector, in a CGE model environment. Airaudo et al. (2023) show how increasing polluting energy prices ramps-up the clean energy investment and raises the share of green energy generation, in a standard New Keynesian DGSE model for a small open economy.

3 Model

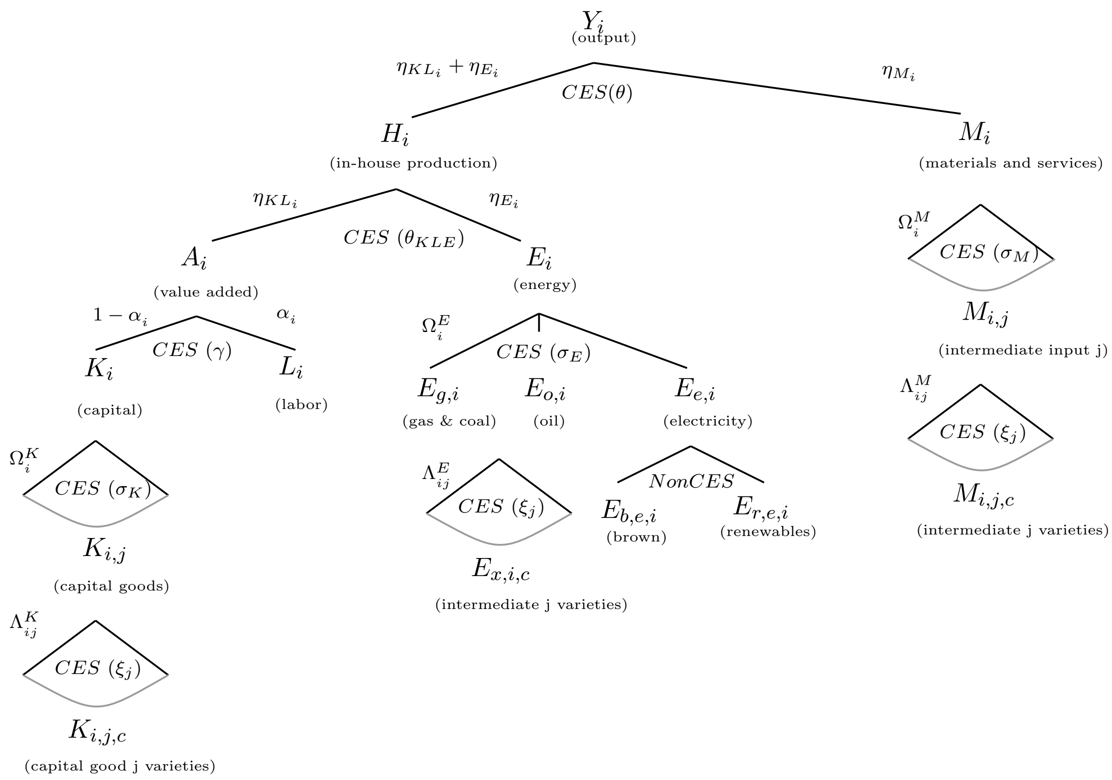
We analyze the impact of the introduction of a tax on polluting inputs through a multi-country production and investment network model augmented with an energy block. This model captures the various relationships among sectors in different economies. Figure 1 graphically illustrates the production function of the firms. First, the model represents a global economy in which sectors in each country use the output generated by other national and foreign sectors as inputs for the own production.[4] Thus, firms shift their demand away from the most polluting sectors due to the increase in relative prices following the implementation of the tax. Moreover, firms also use more imported good from countries with laxer environmental taxation. Second, the model considers the relationship among sectors in the supply of capital goods.[5] Hence, the impact of environmental taxation is reflected also through the accumulation process of capital in the economy, affecting both investment incentives and the costs of sectors producing capital goods. Finally, our model includes a renewable energy sector, which development is endogenous to the changes in energy costs. The growth of renewable energy impacts the economy through the investment network by increasing demand for investment goods for its installation and reducing energy costs, benefiting other sectors through the production network.

This model enables us to analyze the impact of different environmental tax specifications on the total CO_2 emissions of different sectors in each country, as well as to decompose the contribution of each mechanism. The impact of the tax can firstly affect CO_2 emissions by changing the aggregate level of production. Also, given a certain level of production, the relocation of production towards sectors with lower taxation due to their lower carbon footprint helps reduce emissions. Furthermore, within each sector's production, the model also captures how the combination of inputs used by each sector changes. Lastly, the model allows us to calculate the effect of carbon leakage. Conditioned on

[4] See Baqaee and Farhi (2024) as a seminal reference.
[5] See Vom Lehn and Winberry (2022) as a seminal reference.

the production level of each sector and their adjustments in consumed inputs, we can calculate the additional variation that would occur if the geographic origin of supplied inputs were not changed.

Figure 1: Firms production function



3.1 Firms

Within each of the $\mathcal{C}$ countries there are $\mathcal{S}$ firms, each of them producing the local variety of one of the sectors, $Y_{s,c}$.[6] To produce their output, firms transform labor (L), capital (K), energy (E) and other intermediate inputs (M), combined with a level of productivity (Z). Each of the representative firms is competitive and sells its output equal to its average cost.[7]

Firms produce following a nested CES function with constant returns to scale. The production function has the form $((KL)E)M)$. In the first nesting level, firms create value added by combining capital and labor. Then, to operate the value-added component (A), firms need energy, which is complementary to the capital-labor bundle. In a final nesting level, firms combine the capital-labor-energy (H) component with intermediate inputs purchased from the other sectors.[8]

[6] See Table A.3 for a the classification of 44 industries.

[7] In Section 3.1.1 we discuss that to reflect the marginal pricing of the electricity sector in European markets, we assume that the price of the firms in that sector is set according to the change in fossil fuel prices. Thus, this is the only sector in which there are economic profits.

[8] For the sake of clarity, we omit the time subscript where it does not provide additional information.

$$Y_i = Z_i \cdot \left[(\eta_{KL} + \eta_E) \cdot H_i^{\frac{\theta-1}{\theta}} + \eta_M \cdot M_i^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \tag{1}$$

where η_{KL}, η_E and η_M are the average share of value added, energy expenditure and material expenditure over total production of the firm. θ is the elasticity with which firms can substitute the home-produced capital-labor-energy component with intermediate inputs bought from other firms.

$$H_i = \left[\left(\frac{\eta_{KL}}{\eta_{KL} + \eta_E} \right) A_i^{\frac{\theta_{KLE}-1}{\theta_{KLE}}} + \left(\frac{\eta_E}{\eta_{KL} + \eta_E} \right) E_i^{\frac{\theta_{KLE}-1}{\theta_{KLE}}} \right]^{\frac{\theta_{KLE}}{\theta_{KLE}-1}} \tag{2}$$

$$A_i = \left[\alpha \cdot L_i^{\frac{\gamma-1}{\gamma}} + (1-\alpha) K_i^{\frac{\gamma-1}{\gamma}} \right]^{\frac{\gamma}{\gamma-1}} \tag{3}$$

The relationship between the value of θ and θ_{KLE} contains an important mechanism for how a tax that makes the price of energy inputs more expensive operates in the model. First, a value of $\theta_{KLE} < 1$ implies a complementarity between capital and labor use and energy consumption. An increase in energy costs would also imply a higher cost of operating firms' capital, reducing the value of capital to firms and leading to stranded assets. For its part, the value of θ shows the sectors' ability to substitute their own production for intermediate inputs purchased from other firms. A higher value of θ would imply that, in the face of an increase in energy costs, companies will tend to make up for the fall in their own production by purchasing inputs produced by other sectors.

Intermediate Inputs and Energy The bundles of energy and intermediate inputs are, in turn, a combination of the output of other sectors. First, the energy component is the combined energy sources produced by the Energy Mining (D05T06), Refined Petroleum Products (D19) and Electric Power (D35) sectors. The intermediate materials component is a bundle consisting of the rest of the non-energy sectors of the economy. Thus, the consumption of energy (E_i) or intermediate materials (M_i) of a sector i is the combination of different types of goods and services with an elasticity of substitution of σ_E or σ_M

$$X_i = \left(\sum_{j=1}^{S^X} \Omega_{i,j} X_{i,j}^{\frac{\sigma_X-1}{\sigma_X}} \right)^{\frac{\sigma_X}{\sigma_X-1}} \quad \text{for } X = \{M, E\} \tag{4}$$

where the element (i, j) of matrix Ω represents the importance of goods from sector j for sector i.

In addition, in the consumption of each good, firms combine the different domestic varieties produced, combined with an elasticity of

$$X_{ij} \quad = \quad \left(\sum_{h=1}^{C} \lambda_{ijh}^{X} X_{ijh}^{\xi_j - 1/\xi_j} \right)^{\frac{\xi_j}{\xi_j - 1}} \tag{5}$$

where λ_{ijh} represents the initial share of expenditure by firm i on the variety of good j produced in country h.

Capital and Investment. Each sector accumulates capital for the following period. To produce the set of capital, each sector invests in a set of investment goods produced by the other sectors of the economy. The process of capital accumulation is

$$K_{i,t+1} \quad = \quad (1 - \delta_i) \cdot K_{i,t} + I_{i,t} - \frac{\varsigma}{2} \left(\frac{K_{i,t+1}}{K_{i,t}} - 1 \right)^2 \cdot K_{i,t} \tag{6}$$

where δ_i is the rate of depreciation of sector i's capital stock. Firms face convex adjustment cost to change their level of capital.

Similar to intermediate inputs, each sector i combines the investment goods produced by the rest of sectors j with a function of

$$I_i \quad = \quad \left(\sum_{j=1}^{S} \Omega_{i,j}^{K} \cdot I_{i,j}^{\frac{\sigma_K - 1}{\sigma_K}} \right)^{\frac{\sigma_K}{\sigma_K - 1}} \tag{7}$$

where the element (i, j) of matrix Ω^K represents the importance of investment goods from sector j for sector i.[9]

Labor. Labor is imperfectly mobile across sectors with an elasticity υ. The amount of labor in each sector is

$$L_i \quad = \quad \omega_L \left(\frac{W_i}{W_c} \right)^{\upsilon} \cdot L_c \tag{8}$$

where L_c is the quantity of labor in country c, as a function of the aggregate wage.

Investment. Capital goods are durable and their stock in a given period ($K_{icjc',t+1}$) depends both on the non-depreciated stock of the previous period ($K_{icjc',t}$) and on the investment of the previous period ($I_{ijc,t}$).

[9] See Quintana (2025b) for a description of the building of the investment matrix Ω^K.

$$K_{icjh,t+1} = (1-\delta_j) \cdot K_{icjh,t} + I_{icjh,t} \tag{9}$$

Therefore, the equilibrium condition for the investment decision equates the price of the capital good of sector j from country c' for firm i in country c with the discounted returns that such firm will get from it

$$P_{icjc',t} = \sum_{z=1}^{\infty} \left(\frac{(1-\delta_j)^{z-1}}{\Pi_{s=1}^{z}(1+i_{c,t+s})} R_{icjc',t+s} \right) \tag{10}$$

where the flow of nominal returns that the asset produced by sector j in country c will produce ($R_{icjc',t+s}$) for the sector-country firm i, discounted at the nominal interest rate ($i_{c,t+s}$) for each period and the depreciation rate (δ_j), must equal the price of the asset ($P_{icjc',t}$). Therefore,Equation (10) shows the additional contribution of networks to the capital accumulation process, as the shocks to the capital supplier sectors will also affect the required returns of assets they supply.

Labor. Labor is imperfectly mobile across sectors and firms face a specific labor supply curve

$$L_i = \omega_i^L \left(\frac{W_i}{W_c}\right)^{\upsilon} \cdot L_c \tag{11}$$

where L_i is the amount of employment of a sector in country c, W_i is the wage offered by the firm, and W_c and L_c are the average wage and total employment in country c. The initial share of employment of each sector is given by ω_i^L . Elasticity υ determines the mobility of labor across sectors and, implicitly, determines the dispersion of wages. Very large values of υ impose almost perfectly mobility and wage equalization across sectors.

Given the average nominal wage, companies in a country face a labor supply curve that reflects the imperfect mobility of labor between different sectors.

$$L_{i,c} = \omega_{i,c}^L \left(\frac{W_i}{W_c}\right)^{\upsilon} \cdot L_c \tag{12}$$

where $L_{i,c}$ is the amount of employment of a sector i in country c, $W_{i,c}$ is the wage offered by the firm, and W_c and L_c are the average wage and total employment in country c. The initial share of employment of each sector is given by $\omega_{i,c}^L$. Elasticity υ determines the mobility of labor across sectors and, implicitly, determines the dispersion of wages. Very large values of υ impose almost perfectly mobility and wage equalization across sectors.

3.1.1 Electricity market and renewable energies

Electricity market. Firms use an energy bundle in their production. This bundle combines four energy sources; three fossil fuels (coal, natural gas, and oil) and electricity. The energy sources are combined under a constant elasticity of substitution and the importance of each source j is specific to each industry i. In the model, the importance of each energy source is calibrated as a percentage of the energy expenditure of each industry i in sectors D05, D06, D09 and D35. In addition, from the information in the world input-output tables, we can determine the country supplying each fossil fuel.

Renewable energies. We extend the model to allow for the existence of two electricity suppliers within each country: fossil fuel based and green. Fossil fuel based electricity production follows a standard production function, using both capital and labor as well as intermediate inputs and fossil fuels from the other energy sectors. Thus, fossil fuel based electricity production has positive marginal costs equal to the cost of fossil fuels, and its production can be flexibly expanded within each period by purchasing more fossil fuels.

In contrast, the production of green electricity requires only capital. Therefore, it has no marginal cost, but its production capacity in a given period is constrained by investments made in previous periods.

$$Y_{c,t}^{R} = K_{c,t}^{R} \tag{13}$$

A critical difference between the two types of electricity is their availability. While fossil fuel based power can be supplied at will at any time of the year to meet demand, the distribution of green power is fixed and cannot be adjusted to meet demand at any time. Therefore, the relative value of producing the two types of electricity is different.

We model the electricity market in a way that reflects two fundamental features: the pass-through of commodities into the price of electricity and the different remuneration of green and fossil fuel based electricity. These features are the result of the marginalist pricing system prevalent in most European economies. In a marginalist market, the price of electricity is equal to the marginal cost of the most expensive technology needed to meet demand at that time. Given this price, all electricity suppliers receive the same price, regardless of their costs. However, the price is not the same at different times of the year.

Conditioned to a given moment in time, electricity from renewable or fossil fuel sources are perfectly substitutable and, given the marginalist system always receives the same price. However, by its very nature, renewable production is not homogeneous over time, but tends to be concentrated at certain times of the day and seasons and is not dispatchable. This results in the average price received for electricity produced by renewables not being equal to that received for fossil fuel based electricity. This relationship is modeled in Equation (14).

$$P^R_{c,t} = P^B_{c,t} \cdot \left(1 - S^{\varrho}_{c,t}\right) \tag{14}$$

where P^R is the price that renewable energy receive, P^B is the price that fossil fuel based electricity receive and S is the share of renewable energy over total electricity generation. Parameter ϱ sets the concavity of the capture price factor, $\varrho > 1$. [10] [11]

Equation (14) with the parameter $\varrho > 1$ implicitly assumes that the two types of electricity are substitutes at an annual frequency with a non-constant elasticity of substitution. If the percentage of renewable generation is very limited and therefore fossil fuel based generation is still needed at all times of the year, an increase in the annual percentage of green generation will reduce fossil fuel based generation by one. Therefore, for small values of S, the implicit elasticity of substitution between the two types of electricity is infinite, and therefore the price received for both is the same.

However, if the annual average of renewable generation is high, and given the non-homogeneity in the time profile of production, this implies that there are periods of the year when fossil fuel based power is not needed. Thus, an increase in green generation does not reduce fossil fuel based generation in a perfectly proportional way. Thus, in the extreme cases with very high percentages of green generation, renewable and fossil fuel based electricity are used in completely separate periods of the year, implying a minimal elasticity of substitution. Thus, as the annual percentage of green generation increases, an increase in green generation reduces its value because it occurs at times when electricity demand is already saturated.

Therefore, the decision to invest in renewable energy is determined by the price of electricity from non-renewable sources and by the percentage that renewable producers capture. The initial increase in energy costs due to the introduction of environmental taxes increases the incentives to increase the share of renewable generation to the point where the increase in the marginal price of electricity is offset by the fall in the capture share due to market cannibalization among renewables.

[10] The most illustrative example of the concept captured by Equation (14) is the case in which renewable generation is sufficient to cover the total demand during certain hours of the day. Assuming that this proportion of hours is increasing in the amount of installed renewable generation, say S^{ϱ}, renewable electricity producers would receive only S^{ϱ} times the price that prevails in all other hours, namely P^B.

[11] See Quintana (2025a) for a discussion of its parametrization.

3.2 Households

In every country there is a representative household which owns all the firms in the country and supplies labor. Households' preferences are represented by the function

$$U = \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left(\log C_t - \frac{L_t^{1+1/\mu}}{1+1/\mu} \right) \tag{15}$$

where μ is the Frisch elasticity of labor supply and β the discount factor.

$$C_i = \left(\sum_{j=1}^{S} \Omega_{i,j}^C C_{c,j}^{\frac{\sigma_C - 1}{\sigma_C}} \right)^{\frac{\sigma_C}{\sigma_C - 1}} \tag{16}$$

where the (i, j) element of matrix Ω^C represents the importance of goods from sector j on the basket consumption of country's i household.

Also, within the consumption of a given good j, households combine the different domestic varieties produced in each country, combined with an elasticity of ξ_j

$$C_{ij} = \left(\sum_{h=1}^{C} \lambda_{ijh}^C C_{ijh}^{\xi_j - 1/\xi_j} \right)^{\frac{\xi_j}{\xi_j - 1}} \tag{17}$$

where λ_{ijh}^C represents the share of expenditure by the household in country i on the variety of good j produced in country h.

The household budget constraint states that households in each country derive their income from wages, income from the country's firms and the lump-sum rebate of carbon tax revenues. Households use their income for capital investment in the country's firms and final consumption.

$$P_c^C \cdot C_c + P_c^K \cdot I_c = W_c \cdot L_c + \Pi_c + \tau_c \tag{18}$$

where P_c^C is the price of the consumption-bundle for country c household, C_c is aggregate consumption, P_c^K is the price of the investment-bundle for country c firms, I_c is aggregate investment, W_c is average wage across sectors, L_c is aggregate employment, Π_c is the revenue of country c firms -discounted of wages and intermediate inputs-, and τ_c is the lump-sum rebate.

3.3 Equilibrium

Given that each country's household owns all the labor and firms, their budget constraint is set by labor and capital payments, the rebate of the taxes and the profits of the electricity sector. The output of each firm is used to be consumed by the households of individual households, used as intermediate inputs of other sectors or invested as capital goods of other firms. Finally, the sum of the labor demand of the sectors in each country equals the labor supply of the representative household of the country.

4 Calibration and data sources

The main calibrated parameters of the model are taken from the literature and are listed in Table A.1 in the Appendix. On the other hand, multiple data sources are used for this analysis, which are described in detail below.[12]

Increase in fossil fuel prices derived from the carbon tax. To calculate how the carbon tax on polluting inputs translates into the price increase in the sectors producing fossil fuels,[13] we rely on the World Input-Output database from the OECD and information from the International Energy Agency (IEA), EXIOBASE and Eurostat. First, we calculate the increase in coal, natural gas and oil prices, taking the energy prices of 2018 IEA (2022) as the starting price before the tax. Second, we determine the increase in the price of the sector related to the production of fossil fuels, D05T06 -Mining and Quarrying, energy producing products- by calculating the weighted value of production coal, natural gas and oil in each economy. Fossil fuels production and consumption data comes from the World Energy Statistics and Balances (IEA, 2023).

Coexistence with the EU ETS. As the proposed carbon tax would affect the whole economy, the sectors that already belong to the EU ETS mechanism must be compensated to avoid double taxation. This adjustment is not quantitatively relevant, as prices in the ETS markets were less than €16 per tonne in 2018. In any case, we reimburse all sectors pertaining to the EU ETS in each EU country, considering their respective verified GHGs emissions and the ETS price, independently if the emissions allowances were freely allocated or acquired. EU ETS price is obtained from European Energy Exchange and GHGs emissions by sector and country under the EU ETS from the European Environment Agency.

[12] Table A.2 in the Appendix summarizes the data sources employed in this work.

[13] CO_2 emissions per physical unit of polluting input have been obtained from the information provided by the US Energy Information Administration.

EU carbon border adjustment. Note that intra-EU trade is not part of the carbon adjustment scheme. To calculate the surcharge on extra-EU imports equivalent to the carbon tax, we rely again on the global input-output model based on World Input-Output database from the OECD (2021b), which allow us to calculate the emissions embedded in imports to each EU country. Applying the carbon tax of €100 per tonne emitted to emissions embedded in imports, we obtain the sector and importer specific tariff to extra-EU imports.

GHGs emissions in production and in consumption. To calculate on the GHGs emission reduction in production and embedded in the final demand, we use the database the OECD's Trade in embodied CO_2 (OECD, 2021b) for the year 2018 which is consistent with the OECD's World Input-Output database.

5 Results

The aim of this exercise is to analyse the economic and environmental consequences of the extension of the EU carbon pricing initiatives under alternative carbon border adjustment schemes. We introduce an incremental carbon price of €100 per tonne in all EU countries.[14] We consider in addition the effect of border adjustment mechanism in the EU, introduced as equivalent surcharge on EU imports according to their carbon content.

For the shake of simplicity, we show the impact of these two specifications (with and without CBAM) at different time horizons. First, we focus on the short-run effects, characterized by households and firms adjusting their demand of inputs and final products of sector according to the price changes induced by the carbon prices but, there is neither adjustment in the investment decisions by firms nor renewable deployment. We then consider the additional medium-run case, in which firms adjust their capital levels, including in the renewable energy sector.

The environmental and economic effects are shown, both at an aggregate and sectoral level. Results are reported in terms of changes in induced emissions and carbon leakage, GDP, consumption, investment, trade and inflation.

The intuition behind the results is as follows. In the short term, firms and households adjust their demands to the new prices but firms cannot adapt their investment decisions. The imple-

[14] Additional exercises have been also conducted utilizing alternative carbon prices paths. An incremental carbon price of €100 has been adopted as the baseline for our analysis, as this level should be reached in the short to medium term to achieve climate outcomes aligned with the Paris Agreement, according to NGFS scenarios (see NGFS, 2023).

mentation of the carbon tax and the CBAM lead to an increase in input costs, particularly in energy costs, which are subject to higher taxation due to their greater carbon content. In this new situation, European producers and households reduce their consumption of carbon intensive inputs and goods, respectively, to mitigate the increase in costs. In absence of a carbon adjustment, this process also leads to a substitution of domestic production with (polluting) imports from third-countries.

These changes reduce the return on capital for European companies in two ways. Firstly, because of the fall in demand caused by the increase in firms' costs. Secondly, given the complementarity between energy and capital, the carbon tax also increases the cost of using the latter. Therefore, companies would like to reduce their capital stock. The impossibility of doing so in the short term leads to the emergence of stranded assets, that is, capital goods that are no longer used and may end up as a liability before the end of their expected economic life.

To analyze the impact of environmental taxation in the medium term, we explore the results of two model specifications: with and without renewable energies deployment. Considering endogenous investment in renewable electricity reduces the economic impact of the increasing carbon prices. When investment in renewables is considered, through an endogenous response to higher energy prices, the demand for investment in renewables increases, expanding the 'green' energy production and, then, the hike in energy costs caused by the increase in carbon prices is partially undone. Conversely, if investment in renewables is not considered, the fall in short-term return on capital resulting from the carbon tax leads companies to reduce their investment, which exacerbates the negative short-term economic impact.

The stark difference between these results with and without renewables shows the key relevance of this factor in assessing the medium-term consequences of the environmental fiscal reforms.

5.1 Short term effects

The increase in carbon prices leads to an increase in the price of polluting inputs and, thus, in the production costs of European producers. This is initially reflected in an increase in inflation faced by households, which reduces their consumption and results in a decrease in GDP. This has an immediate effect on economic performance both in terms of the higher consumption prices faced by local consumers and the loss of competitiveness of European producers. Table 2 shows the short run effects.

Overall, given the increase in carbon prices, real GDP in the EU would be 1.4% lower and CPI 0.7% higher. An important contribution to this result comes from international competition. The EU trade balance in real terms, excluding energy products, would deteriorate significantly. However, given the importance of raw materials in the European import basket, once these are taken into account the trade balance is rebalanced.

When introducing the border adjustment that levies taxes on imports, a shift from foreign to domestic production occurs, but it is insufficient to compensate in GDP terms for the additional increase of the price of intermediate inputs such as metal, plastic, and chemicals, which are highly polluting and subject to the import tariffs (see also Hinterlang (2024)). Consequently, the industries that are more integrated into global value chains, such as machinery and transportation, are most affected. Overall, the decrease in GDP is greater than that resulting from a carbon tax alone, although the environmental outcome improves (as explained below). This is a somewhat novel finding of this model as it captures inter-linkages and network effects that are missing in more aggregated approaches, avoiding the upward bias of considering only the positive effect of substituting imports with domestic production.

Sector analysis. In terms of sectoral breakdown, since carbon prices increase the energy costs, in the absence of any form of carbon adjustment, it leads to the substitution of local production by imports. Sectors that are most affected are very energy-intensive, such as energy production, transport (oil consumption) and metals, chemicals, etc., which use of natural gas among other energy sources. These sectors tend to be upstream in the value chain, so their price increase is translated to the rest of the economy. EU producers react replacing local suppliers with foreign ones, resulting in a lower cost increase. Thus, the carbon leakage mainly affects the most energy-intensive and most polluting sectors. When the import tariff is included, both foreign and local producers are affected by the carbon tax, and there is lower substitution by imports in the most energy-intensive sectors, benefiting local producers of these energy-intensive goods. However, the impact on the rest of the economy is larger since other sectors cannot avoid the local carbon tax by buying cheaper polluting and energy-intensive inputs from abroad. In this case, the most affected sectors are cars, machinery, and electronic equipment, which use inputs from metal, chemical sectors, among others, that are highly intensive in energy. Table 2 shows the most and least affected sector by the introduction of the carbon tax as well as those which benefit from the introduction of the CBAM.

Environmental accounting. The increase in carbon prices leads to a reduction in total emissions, although this result is the outcome of several mechanisms, some of which have opposite effects. The most immediate effect of the carbon prices rise is a decrease in emissions due to a reduction in production. In the scenario considering a carbon price increase instrumented through a carbon tax, of the overall reduction in the EU carbon footprint, 7.1%, this mechanism accounts for 1.4% (around one fifth of the effect). Within this decrease, an essential component is sectoral reallocation. The sectors that are most dependent on fossil fuels and energy, such as metal or chemical production, have the highest reduction in demand, which, even with a reduced aggregate production, adds a 3.0% drop in emissions. Moreover, within the production of each sector, energy consumption decreases due to input substitution, although technical limitations constrain it, specially in the short run. Because energy inputs produce a greater carbon footprint, this change adds an additional impact to the reduction of emissions of 1.0%. However, the imposition of the carbon tax may unintentionally cause European and non-European producers and households to substitute inputs and goods, respectively, previously purchased from EU suppliers with extra-EU production, which are more polluting than their European counterparts. This substitution effect accounts for carbon leakage, would result in an additional 1.4% lower reduction in emissions if EU production would have not moved abroad.

To mitigate the carbon leakage by introducing the CBAM leads to a reduction of the carbon footprint almost 1 percentage point larger. It is worth noting that this reduction is accompanied by a larger drop in GDP due to the import surcharge. However, the cost/benefit ratio is an additional 0.84% reduction in emissions for a 0.13% drop in real GDP, which is significantly lower than that of the carbon tax. This difference can be attributed to the fact that the most polluting products produced abroad are also taxed, leading to a reduction of emissions due to changes in the mix of inputs from 1.05% to 1.84% with the border adjustment. Additionally, since European production tends to be cleaner, the border adjustment, by increasing relatively the EU demand, reduced carbon leakage from 1.4% to 0.5% of GHGs emissions.

Finally, an additional effect is the emissions from the rest of the world rise. On top of to the shift of part of EU's production to third countries, the model also takes into account the so-called fossil fuel price channel. The imposition of the carbon tax entails a reduction in the global consumption of polluting energy commodities, and therefore their price on the world market drops. This leads to an increase in their consumption in non-European countries, which are not exposed to the tax.

Table 1: Short term impact

	European Union		Rest of the World	
In percentage	CT	CBAM	CT	CBAM
Real GDP	-1.41	-1.54	-1.72	-1.53
Nominal GDP	-1.04	-1.06	-1.33	-1.04
CPI	0.67	0.85	0.78	0.86
Exports	-1.44	-1.84	-3.29	-1.51
Exports (ex. Energy)	-1.05	-1.42	-2.88	-1.57
Imports	-1.61	-2.96	-3.32	-2.56
Imports (ex. Energy)	-0.03	-1.32	-1.68	-1.23
Export price	0.82	1.02	1.89	0.82
Export price (ex. Energy)	0.59	0.78	1.64	0.86
Import price	2.16	3.24	3.27	3.23
Import price (ex. Energy)	0.02	0.94	0.98	0.93
Tax revenue	0.55	0.72	0.71	0.48
Labour	-0.7	-0.73	-0.96	-0.75
CO_2 emissions	-7.09	-7.06	-7.36	-6.52
Carbon footprint (production)	-5.72	-6.56	-6.9	-6.28
Carbon leakage (production)	1.37	0.5	0.46	0.24
CO_2 reduction contribution				
due to production level	-1.42	-1.55	-1.74	-1.55
due to sectoral reasignment	-2.99	-2.89	-2.98	-2.54
due to inputs substitution	-1.05	-1.84	-1.89	-1.93
due to electric sector emissions	0	0	0	0
Carbon footprint (consumption)	-5.97	-7.48	-7.65	-7.42
Carbon leakage (consumption)	1.12	-0.42	-0.29	-0.9
Electricity price	17.11	18.56	18.55	18.67
Renewable change	0	0	0	0
CO_2 emissions (World)	-0.44	-0.54		
due to production level	-0.12	-0.16		
due to sectoral reasignment	-0.15	-0.19		
due to inputs substitution	-0.09	-0.15		
due to electric sector emissions	0	0		

CT= Carbon tax, CBAM= Border tax, ex= excluding.

Table 2: Change in value added of the 10 most and 10 least affected sectors by a €100 carbon price (in percentage change)

A. Change in value added with CT (no CBAM)

Most affected		VA	CO_2	Least affected		VA	CO_2
D35	Electricity and gas	-6.32	-7.17	D84	Public Admin.	-0.32	-6.96
D05T06	Mining (energy)	-6.13	-3.54	D41T43	Construction	-0.28	-3.97
D19	Coke	-4.77	-10.78	D26	Electronic equipment	-0.27	-3.65
D51	Air transport	-2.3	-1.93	D29	Motor vehicles	-0.25	-4.39
D09	Mining other	-1.61	-5.24	D61	Telecommunications	-0.25	-6.89
D24	Basic metals	-1.23	-3.55	D85	Education	-0.22	-7.18
D50	Water transport	-1.23	-1.5	D30	Other transport equipment	-0.22	-3.54
D49	Lad transport	-1.23	-5.41	D86T88	Health and social work	-0.21	-6.28
D07T08	Mining (non-energy)	-1.19	-5.92	D21	Pharmaceuticals	-0.2	-3.17
D20	Chemical products	-1.1	-5.98	D68	Real estate	-0.03	-6.85

B. Change in value added of the CT + CBAM respect to only CT scenario

Most affected		VA	CO_2	Least affected		VA	CO_2
D27	Electrical equipment	-0.13	-1.79	D53	Postal	0.12	-0.9
D35	Electricity and gas	-0.11	-0.49	D31T33	Manufacturing	0.17	-1.27
D25	Metal products	-0.1	-2.01	D49	Lad transport	0.19	-0.42
D29	Motor vehicles	-0.08	-1.5	D22	Rubber and plastics	0.27	-1.01
D28	Machinery and equipment	-0.08	-1.57	D23	Non-metallic mineral products	0.32	-0.38
D26	Electronic equipment	-0.07	-1.2	D07T08	Mining (non-energy)	0.32	-0.54
D13T15	Textiles	-0.07	-1	D05T06	Mining (energy)	0.44	-0.11
D30	Other transport equipment	-0.06	-1.26	D50	Water transport	0.59	-0.19
D19	Coke	-0.06	-0.51	D24	Basic metals	1.16	-0.5
D10T12	Food, beverage and tobacco	-0.06	-0.85	D51	Air transport	1.55	0.1

CT= Carbon tax, CBAM= Border tax.

5.2 Medium term effects. The role of renewable energies

The medium term consequences of the carbon pricing depends heavily on how the substitution between polluting and clean energy proceeds and how investment turns into the availability of clean energy. In this regard, we considered the implications of two alternative model specifications, one with endogenous investment in renewable energy electricity and one without it to better understand the role of renewables in this framework.

One of the intended effects of the carbon tax is to increase the cost of fossil fuels, which translates to higher electricity costs, given that technologies to generate electricity with polluting inputs tend to set the electricity price. Investment in renewable energy reacts endogenously to the increase in electricity prices, leading to an increase in renewable energy capital and production (see Section 3.1.1).

The positive contribution of renewable energy comes through two channels. First, the installation of renewable capacity provides a significant positive demand shock, which is then transmitted to the rest of the economy through the investment network. In addition, the increase in the share of renewable energy and the reduction in the consumption of energy from fossil sources partially alleviates the increase in the price of electricity, which is passed on to the rest of the economy through the production network. In the medium term, as electricity becomes relatively cheaper to the polluting energy sources, the economy will experience a process of electrification, resulting in a shift in consumption from polluting energy to electricity in sectors other than electricity, reinforcing the achievement of climate goals and reducing the negative macroeconomic effects of the carbon tax.

According to our results, renewable deployment is key for achieving large reduction goals and minimize the economic costs of the transition policies. In total, GDP in the medium term with renewable energy would be only 0.4% lower than in the absence of the carbon tax, so the short term negative impact of the environmental taxation is reduced by more than 70%. On the other hand, emissions would be up to 24% lower, which would quadruple the savings achieved in the short term. The presence of renewables mitigates the energy cost increase for EU producers, the magnitude of import substitution is clearly smaller and, therefore, the carbon leakage is also lower. In this framework, the gains of introducing carbon adjustment are also more limited. Table 3 contains all the information on the aggregate changes in the medium term scenario.

The significant difference between the results with and without renewable energy underscores that neglecting the renewable energy investment significantly overestimates the adverse impact on environmental tax reforms economic activity and underestimates their capacity to reduce GHGs emissions.

Table 3: Medium term impact

	European Union				Rest of the World			
	Renewables		No Renewables		Renewables		No Renewables	
In percentage	CT	CBAM	CT	CBAM	CT	CBAM	CT	CBAM
Real GDP	-0.41	-0.61	-2.22	-2.55	-0.15	-0.19	-0.14	-0.18
Nominal GDP	0.23	0.28	-1.3	-1.37	-0.09	-0.13	-0.02	-0.06
CPI	0.97	1.27	1.29	1.62	0.12	0.13	0.17	0.18
Exports	-1.75	-2.42	-2.21	-2.91	-3.89	-5.14	-1.88	-3.09
Exports (ex. Energy)	-1.37	-2.02	-1.79	-2.46	-1.22	-2.46	-0.28	-1.51
Imports	-3.89	-5.14	-1.88	-3.09	-1.75	-2.42	-2.21	-2.91
Imports (ex. Energy)	-1.22	-2.46	-0.28	-1.51	-1.37	-2.02	-1.79	-2.46
Export price	1.02	1.36	1.3	1.67	2.21	3.24	2.32	3.36
Export price (ex. Energy)	0.81	1.13	1.05	1.4	0.1	1.04	0.17	1.1
Import price	2.21	3.24	2.32	3.36	1.02	1.36	1.3	1.67
Import price (ex. Energy)	0.1	1.04	0.17	1.1	0.81	1.13	1.05	1.4
Tax revenue	0.51	0.67	0.55	0.71	0	0	0	0
Labour	-1.13	-1.31	-1.13	-1.33	-0.09	-0.11	-0.1	-0.12
CO_2 emissions	-23.98	-24.64	-7.89	-8.25	0.83	0.76	0	-0.09
Carbon footprint (production)	-23.12	-24.42	-6.6	-7.45	0.87	0.81	-0.1	-0.17
Carbon leakage (production)	0.86	0.22	1.29	0.81	0.03	0.05	-0.1	-0.09
CO_2 reduction contribution								
due to production level	-0.42	-0.61	-2.25	-2.58	-0.15	-0.19	-0.14	-0.18
due to sectoral reasignment	-6.69	-6.77	-3	-3	0.17	0.14	0.09	0.07
due to inputs substitution	-6.14	-6.8	-1.08	-1.55	0.16	0.16	-0.05	-0.06
due to electric sector emissions	-10.81	-11.23	0	0	0.68	0.69	0	0
Carbon footprint (consumption)	-26.4	-28.41	-7.2	-8.64	0.91	0.86	-0.34	-0.41
Carbon leakage (consumption)	-2.41	-3.77	0.69	-0.39	0.08	0.11	-0.34	-0.32
Electricity price	7.38	7.8	17.55	19.04	0.29	0.29	0.05	0.05
Renewable change	35.8	37	0	0	-1.6	-1.63	0	0
CO_2 emissions (World)	-1.11	-1.23	-0.62	-0.73				
due to production level	-0.17	-0.22	-0.31	-0.37				
due to sectoral reasignment	-0.37	-0.4	-0.15	-0.17				
due to inputs substitution	-0.33	-0.38	-0.13	-0.17				
due to electric sector emissions	-0.22	-0.24	0	0				

CT= Carbon tax, BT= Border tax, Retal.= Border tax and Retaliation, Subs.= Border tax and Exports Subsidy, ex= excluding.

6 Conclusions

In this work, we analyze the environmental and economic consequences of the extension of the EU carbon pricing initiatives to all economic sectors considering carbon border adjustment by constructing a network model with a detailed representation of the energy sector.

Renewable energy deployment generates larger GHGs reduction and minimize the economic costs of the transition policies. The increase in energy prices, driven by carbon prices, creates an incentive to invest in renewable energy, thereby gradually curbing the rise in electricity prices. In the mid term, once the investment in renewable energies are deployed, the weight of renewables in the electricity mix increases and the relative price of electricity falls encouraging the electrification of all sectors. In our model, we also consider the cannibalization of prices received by the green generation when its capacity increases. All in all, in this set up, economic losses are greatly reduced and it provides a positive environmental outcome. Comparing with a model set up without renewables, its deployment diminishes the negative effect on GDP by around 1.8 percentage points and pushed the reduction carbon footprint by more of 15 percentage points.

This carbon pricing scheme in the EU is a powerful instrument to reduce emissions, mainly through the sectoral reallocation of production and the input switch towards cleaner electricity. With a carbon tax of €100 per tonne, the EU carbon footprint will be reduced by 5.7% in the short run and, in the medium run, once renewable capacity is deployed, will reach 24%. In any case, the unilateral introduction of this policy in the EU leads to carbon leakage.

The introduction of the CBAM curbs carbon leakage but at the cost of larger economic losses. The border adjustment makes energy-intensive sectors with an upstream position as key input suppliers for the other sectors of the economy, such as chemicals or metallurgy, more expensive. The design of the carbon border adjustment must consider the trade-offs between environmental objectives and economic costs. Consequently, the protectionist effect of the CBAM for some sectors results in a loss for the economy at the aggregate level.

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Appendix A. Figures and Tables

Table A.1: Parameters

Variable		Value	Source
σ_E, σ_K, σ_M	Input elasticity across sectors	.2	Baqaee and Farhi (2024); Atalay (2017)
θ	H - M elasticity	.5	Atalay (2017)
θ_{KLE}	KL-E elasticity	.5	Böhringer and Rivers (2018)
γ	K-L elasticity	.9	Atalay (2017)
ξ	Trade elasticity across sector varieties	2	Boehm et al. (2023)
ϱ	Renewable price canibalisation	3	Quintana (2025a)
ς	Capital adjustment cost	.4	Vom Lehn and Winberry (2022)
μ	Frisch elasticity	1	
β	Discount rate	.95	
υ	Labor adjustment cost	1	Horvath (2000)
Ω^X, λ^X, α η	Expenditure shares, and production parameters		ICIO OECD
Ω^K, δ	Investment matrix and dep. rate		KLEMS, ICIO OECD

Table A.2: Data sources

Data	Units	Source
Fossil Fuels prices	Price per tonne of oil equivalent ($)	IEA (2022)
Consumption Fossil Fuels	Tonnes of oil equivalent	IEA (2023)
Sectoral Value Added	Millions $	OECD (2021a)
Emissions CO_2 per sector	Tonnes of CO_2	OECD (2021b)
Border tax	Increase in price (%)	Own calculation
EU ETS reimbursement	% of value of production of each sector	EEX and European Environment Agency

Table A.3: Sector classification

Code	Industry	ISIC Rev.4
D01T02	Agriculture, hunting, forestry	01, 02
D03	Fishing and aquaculture	03
D05T06	Mining and quarrying, energy producing products	05, 06
D07T08	Mining and quarrying, non-energy producing products	07, 08
D09	Mining support service activities	09
D10T12	Food products, beverages and tobacco	10, 11, 12
D13T15	Textiles, textile products, leather and footwear	13, 14, 15
D16	Wood and products of wood and cork	16
D17T18	Paper products and printing	17, 18
D19	Coke and refined petroleum products	19
D20	Chemical and chemical products	20
D21	Pharmaceuticals, medicinal chemical and botanical products	21
D22	Rubber and plastics products	22
D23	Other non-metallic mineral products	23
D24	Basic metals	24
D25	Fabricated metal products	25
D26	Computer, electronic and optical equipment	26
D27	Electrical equipment	27
D28	Machinery and equipment, nec	28
D29	Motor vehicles, trailers and semi-trailers	29
D30	Other transport equipment	30
D31T33	Manufacturing nec; repair and installation of machinery and equipment	31, 32, 33
D35	Electricity, gas, steam and air conditioning supply	35
D36T39	Water supply; sewerage, waste management and remediation activities	36, 37, 38, 39
D41T43	Construction	41, 42, 43
D45T47	Wholesale and retail trade; repair of motor vehicles	45, 46, 47
D49	Land transport and transport via pipelines	49
D50	Water transport	50
D51	Air transport	51
D52	Warehousing and support activities for transportation	52
D53	Postal and courier activities	53
D55T56	Accommodation and food service activities	55, 56
D58T60	Publishing, audiovisual and broadcasting activities	58, 59, 60
D61	Telecommunications	61
D62T63	IT and other information services	62, 63
D64T66	Financial and insurance activities	64, 65, 66
D68	Real estate activities	68
D69T75	Professional, scientific and technical activities	69 to 75
D77T82	Administrative and support services	77 to 82
D84	Public administration and defence; compulsory social security	84
D85	Education	85
D86T88	Human health and social work activities	86, 87, 88
D90T93	Arts, entertainment and recreation	90, 91, 92, 93
D94T96	Other service activities	94,95, 96

Correspondence between sectors in ICIO tables and ISIC Rev.4

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