Can growth take place while reducing emissions?

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Abstract

Do the macroeconomic effect of a carbon tax differ between countries, according to the primary energy source? I answer this question with a theoretical model of directed technical change and test empirically the main results. I find four main results: (i) In the absence of subsidies, carbon taxes have a negative effect on economic growth, (ii) this negative effect is a decreasing function of the proportion of clean energy sources, (iii) subsidies for clean inputs have a positive effect on economic growth, and (iv) the magnitude of this effect grows with the proportion of clean energy sources. The empirical results are consistent with the predictions of the theoretical model, indicating that environmental policies may consider the initial state of the energy mix and the impact of the transition to clean sources on economic growth. **JEL Classification Numbers:** O1, O4, Q4, Q5, O57.

Keywords: Carbon tax, Directed Technical Change, Climate change, and Environment.

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1 Introduction

Tackling climate change without harming economic growth is a major challenge for countries today. While carbon pricing is increasingly recognized as a key policy tool to incentivize emissions reductions, its macroeconomic impacts remain a subject of debate. Experiences with carbon taxes vary significantly across countries, raising questions about the factors driving these differences. For instance, Norway, with its substantial hydropower resources and a high initial share of clean energy in its energy mix, has implemented a carbon tax with relatively limited adverse effects on its economy. Conversely, countries heavily reliant on fossil fuels, such as South Africa, face greater economic adjustment challenges due to their dependence on carbon-intensive industries. This divergence underscores the critical role of a nation's "energy mix"[1] in shaping the macroeconomic consequences of carbon pricing. The energy mix includes both "clean" sources (e.g., hydro, nuclear, solar, and wind power) and "dirty" sources, primarily fossil fuels (e.g., coal, oil, and natural gas). Different energy mixes imply varying degrees of dependence on carbon-intensive industries and disparate adaptation costs associated with transitioning to a low-carbon economy.

This study explores the heterogeneous effects of the energy mix on the macroeconomic impact of carbon taxes, focusing on how the ratio between clean and dirty energy sources shapes GDP growth in the short and long run. Building on the Schumpeterian growth model developed by Acemoglu *et al.* (2012a), I derive theoretical predictions about the role of the environmental policy and energy mix in influencing aggregate production and growth. The model distinguishes between two sectors "clean" and "dirty" and incorporates environmental policies that affect the direction of technological change. Unlike the original theoretical framework, which primarily offers qualitative insights, I extend the analysis by formulating two testable propositions related to income and growth. These propositions are quantitatively validated using empirical methodologies, specifically event studies and local projections, to capture the dynamic responses of economic output to carbon taxation across countries with varying energy profiles.

The findings indicate that, in the absence of targeted clean energy subsidies, introducing a carbon tax often leads to a short-run contraction in economic growth, especially in economies heavily reliant on fossil fuels. However, when the tax is accompanied by subsidies, the effect can be less harmful in the short run and become more favorable as energy sources transition to cleaner

[1]the composition of energy sources used for production and consumption

alternatives in the long run. In addition to these findings, this paper proposes that a portion of the revenue generated by the carbon tax should be allocated to subsidizing clean energy sources to minimize the adverse economic effects of environmental policy. Consistent with previous research[2], the findings highlight that environmental policies can be temporary if they successfully redirect innovation towards cleaner technologies and increase the share of renewable energy sources in the long run, as innovations respond endogenously to changes in policy incentives.

There is substantial literature on the effects of a carbon tax on macroeconomic outcomes, but the findings are unclear. Bernard *et al.* (2018) and Metcalf & Stock (2020) do not find adverse impacts of the carbon tax on aggregate GDP growth or employment in British Columbia, nor in 31 countries in Europe. However, Yamazaki (2017) finds that while British Columbia's carbon tax does not have an adverse effect on employment overall, at the sectoral level the most carbon-intensive and trade-sensitive industries see employment fall, while the clean service and health industries increase employment. Likewise, several authors have studied the distributive effects of the carbon tax on households and have found evidence of regressiveness, by increasing the cost of carbon-intensive products and by changing factor prices (Rausch *et al.* (2011) and Mueller & Steiner (n.d.)). A study by Andersson J (2020) highlights that the Swedish carbon tax, by increasing gasoline prices, has negative effects, especially when measured against annual income. Furthermore, income inequality plays an important role in determining the distributional impact of these taxes.

The literature on the relationship between energy sources, and climate policies is relatively limited. Some studies, such as Papageorgiou *et al.* (2017) estimated the elasticity of substitution between clean and dirty energy inputs within the energy aggregate significantly exceeds unity, which is a favorable condition for promoting green growth. Similarly, Matsumoto (2022), exploring the effect of the carbon tax on the energy source mixes of Japanese households, found that increasing the carbon tax leads to a higher percentage of households using gas and a reduced percentage using electrification.

However, none of the authors have examined how different combinations of energy sources may influence the macroeconomic effects of implementing climate policies, such as the carbon tax, in the short and long run.

This article is also related to a large and growing literature on the environment, resources, and directed technical change. The first contributions (Nordhaus (1993); Stern (2007) and Golosov *et al.*

[2] Fried (2018), Acemoglu *et al.* (2012a)

(2011)) concentrated on the development of theoretical models of climate change and economy, for example, the DICE model that extends the Ramsey growth model. Several economists have developed new theories of economic growth integrating the environmental constraint (Acemoglu *et al.* (2012b), Romer & Romer (2010) and Laffont & Martimort (2009), Torres (2021)). In particular, some authors have analyzed theoretically and empirically how innovations and directed technology drive long-term sustainable growth. For example, Popp (2002) demonstrates that high energy prices encourage cost-saving innovations in the air conditioning industry, and Aghion *et al.* (2012), carried out a similar exercise in the automobile sector.

While there are numerous macroeconomic models, such as those integrating environmental constraints within the context of directed technological change, that explore the broader implications of climate policies. However, as far as I know, the specific relationship between the composition of energy sources, economic growth, and climate policies has not been thoroughly examined. This study aims to fill this gap by empirically demonstrating the model's validity and providing new insights into how different combinations of energy sources influence the macroeconomic effects of implementing climate policies, particularly carbon taxes and subsidies for clean energy.

The remainder of the paper is organized as follows. Section 2 introduces the theoretical model, outlining the propositions regarding the impact of a carbon tax and subsidy on aggregate and sectoral production, as well as growth rates. Section 3 outlines the empirical methodologies employed to estimate the correlation between the carbon tax and GDP growth rate, employment rate, and the variations based on the energy mix composition. Section 4 delves into the presentation and discussion of the empirical findings, along with their implications. Finally, Section 6 provides concluding remarks.

2 Theoretical model

In this Schumpeterian model of directed technological change with environmental constraints, based on Acemoglu *et al.* (2012a) (henceforth AABH), households derive utility from both consumption and environmental quality. Final good production combines clean and dirty energy inputs using a CES production function, where the elasticity of substitution is greater than one, indicating strong substitutability between the two energy sources. Each sector (clean and dirty) produces inputs following the structure of **?**, employing labor and utilizing a range of sector-specific intermediate goods, which are produced by monopolistically competitive firms through innovation. Technological advancements within each sector drive the production of these intermediate goods. While the quality of the environment deteriorates due to the production of dirty inputs, it regenerates at a natural rate. If the rate of environmental degradation exceeds its regeneration rate, it could result in environmental collapse, leading to a halt in production. Taxes and subsidies are employed to steer innovation towards the clean sector, discouraging reliance on dirty inputs, and preventing long-term environmental damage while ensuring sustainable production.

Taxes and subsidies are designed to incentivize innovation in clean sectors while disincentivizing the use of dirty inputs, ensuring sustainable long-term production without surpassing environmental thresholds that could cause irreversible damage. In this study, I extend the AABH framework by analyzing the effects of environmental policies (specifically carbon taxes and clean energy subsidies) on GDP and economic growth, with a particular focus on how the composition of the energy matrix (market size) influences this relationship. The magnitude of these effects is determined by three main factors: (i) the relative levels of technological development in the clean and dirty sectors, both initially and over the long term; (ii) the structure of the policy, including the balance between carbon taxation and subsidies aimed at promoting clean innovations; and (iii) the elasticity of substitution between clean and dirty technologies, although this is not the primary focus of the current research.

2.1 Model with an environmental policy

Environmental policy must ensure that the demand for dirty inputs takes into account the environmental cost of an additional unit of inputs. We model a policy that combines a tax on the dirty sector (τ) and a subsidy on the clean sector ($\phi\tau$). The subsidy is a fraction of the carbon tax revenue allocated to lowering the prices of clean inputs. This policy mix aims to direct low-carbon growth by discouraging production using dirty inputs and accelerating innovation in clean inputs. I assume a balanced budget with an environmental policy, tax revenue must be equal to subsidy spending in clean technology and the resulting can goes to ......?

We assume that each country is inhabited by a continuum of households, consisting of workers and scientists, who can freely switch sectors without incurring adjustment costs. The households have the following preferences:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, S_t) \tag{1}$$

where C_t represents the consumption of the final good at time t, S_t denotes the quality of the environment, and $\rho > 0$ is the discount rate. The environmental quality, $S_t \in [0, \hat{S}]$, where $\hat{S}$ is the baseline level of environmental quality without pollution. Initially, the environmental quality is at its maximum level, $S_0 = \hat{S}$, and in the event of an environmental disaster, it collapses to $S_t = 0$. Environmental quality degrades due to the production of dirty inputs at a rate $\xi > 0$ but regenerates at a natural rate $\delta > 0$. The evolution of environmental quality is expressed by the law of motion:

$$S_{t+1} = (1+\delta)S_t - \xi Y_{dt} \tag{2}$$

Final Good

There is a unique final good, Y_t, produced competitively using "clean" and "dirty" inputs (depending on the primary energy source required).

$$Y_t = \left(Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \right)^{\frac{\epsilon}{\epsilon-1}} \tag{3}$$

The parameter $\epsilon \in (0, +\infty)$ represents the elasticity of substitution between the two sectors. When $\epsilon > 1$, the inputs are considered (gross) substitutes, meaning that the final good production can be achieved by substituting clean energy for dirty energy. For example, renewable energy, assuming it can be efficiently stored and transported, could replace energy derived from fossil fuels (Popp, 2002). Final good producers choose the quantity of each input to maximize profits, solving the following problem:

$$\max_{Y_{dt}, Y_{ct}} \{Y_t - (1+\tau)P_{dt}Y_{dt} - (1-\phi\tau)P_{ct}Y_{ct}\}$$

where Y_{dt} and Y_{ct} represent the quantities of dirty and clean inputs, respectively, and P_{dt} and P_{ct}

denote the prices of these inputs. The parameter τ captures the carbon tax imposed on dirty inputs, while $\phi\tau$ represents a subsidy for clean inputs. Both sectors are assumed to produce their inputs symmetrically under conditions of perfect competition. Using the final good as the numeraire, the price of inputs with the environmental policy is:

$$\left[((1+\tau)P_{dt})^{1-\epsilon} + ((1-\tau\phi)P_{ct})^{1-\epsilon}\right]^{\frac{1}{1-\epsilon}} = 1 \tag{4}$$

The tax is charged on the price paid for each unit of the dirty inputs demanded, while the subsidy is applied as a discount for each unit of clean inputs purchased. Consequently, the relative demand for dirty inputs declines due to the tax, whereas the demand for clean inputs increases as the subsidy reduces their effective prices:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{dt}\cdot(1+\tau)}{P_{ct}\cdot(1-\tau\phi)}\right)^{\epsilon} \tag{5}$$

Clean and Dirty Intermediate Inputs

The two inputs, Y_c and Y_d are produced competitively and sold at the market price to the final good producer[3] . Using L_{jt} labor, A_{jit} the quality of machine i in the sector j, and x_{jit} a continuum of sector-specific machines (intermediates). Given that the market operates under conditions of perfect competition, the optimization problem faced by producers in both sectors involves maximizing profits through the optimal allocation of labor and machines.

$$\max_{x_{jit},L_{jt}} \left\{P_{jt}L_{jt}^{1-\alpha}\left(\int_0^1 A_{jit}^{1-\alpha}x_{jit}^{\alpha}\cdot di\right) - w_{jt}L_{jt} - \int_0^1 p_{jit}x_{jit}\cdot di\right\}$$

From the first-order conditions and by solving the monopolist's problem of maximizing profits, (derived from machine prices minus production costs)[4], we obtain the quantities of inputs produced in each sector as follows:

$$Y_{jt} = \alpha^{\frac{2\alpha}{1-\alpha}}A_{jt}L_{jt}\left(P_{jt}\right)^{\frac{\alpha}{1-\alpha}} \tag{6}$$

[3] In this version, we do not consider the depletion of fossil resources. Although fossil fuel reserves are finite, historical prices have not followed the predictions of the Hotelling model, and scarcity constraints are less relevant in the context of climate change targets (Fried, 2018).

[4] see appendix A

Technological change

At the beginning of every period, all intermediate goods within a sector, begin with the average level of productivity of the previous period. A successful scientist, who has invented a better version of the machine i in sector j increases the quality of the machine by a factor $1+\gamma$ and happens with probability $\eta_j \in (0,1)$. When an innovation is unsuccessful $(1-\eta_j)$, the sector's productivity is equal to that of the previous period. A_{jt-1}.

$$A_{jt} = \begin{cases} \gamma A_{jt-1} & \text{if successful } (\eta_j) \\ A_{jt-1} & \text{if not successful} (1-\eta_j) \end{cases}$$

The problem for entrepreneurs is to maximize the probability of innovating η_{jt} which depends on the price of the patent P_{Ajit}, and R&D investment R_{jt}, that is,$\max_{\eta_{jt}} \{\eta_{jt} P_{Ajit} - R_{jt}\}$. From the first-order condition, we extract the correlation between resources and desired productivity alongside the probability of success. Substituting the probability of success, and given that the price of the patent equals the net profits of the machine producer $P_{Ajit} = \pi_{jit}$, then the probability of innovating in each sector is:

$$\eta_{jt} = 2(1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} P_{jt}^{\frac{1}{1-\alpha}} L_{jt} \tag{7}$$

Equilibrium

Taking the input production equation 6 and the relative input demand equation 5, the ratio between clean and dirty production is expressed in the equation 8. It shows that the tax has no direct impact on production costs, but it does affect the demand for final inputs in each sector. In particular, tax and subsidy increase the demand for clean goods and decrease the demand for dirty inputs.

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{ct}}{P_{dt}}\right)^{\frac{\alpha}{1-\alpha}} \frac{A_{ct}}{A_{dt}} \frac{L_{ct}}{L_{dt}} = \left(\frac{P_{dt} \cdot (1+\tau)}{P_{ct} \cdot (1-\tau\phi)}\right)^{\epsilon} \tag{8}$$

On the supply side of this model, three forces determine the relative benefits of innovation: the *price effect,* the *market size effect*, and the *direct effect of productivity.* In the following, we will see how the tax and subsidy affect each of these.

The price effect means that the less technologically advanced sector tends to have higher prices. As the technological level of the clean sector improves, the price of clean goods decreases. In equilibrium, subsidies for clean production raise the prices of both clean and dirty inputs, while taxes on dirty production lower them. However, since the percentage changes in prices are proportional, environmental policies like subsidies and taxes do not affect the relative price ratio between clean and dirty inputs.

$$\frac{P_{ct}}{P_{dt}} = \left(\frac{A_{dt}}{A_{ct}}\right)^{(1-\alpha)} \tag{9}$$

By substituting the relative prices into equation 8 (see details in the appendix A.2), we can derive the relative labor equilibrium. As a result, the introduction of taxes on dirty inputs and subsidies for clean inputs, while holding all other factors constant, increases wages in the clean sector and reduces them in the dirty sector. This wage differential drives a reallocation of labor towards clean input production, indicating a shift in labor distribution in favor of the clean sector. Where $\varphi = (\epsilon - 1)(1 - \alpha)$.

$$\frac{L_{ct}}{L_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{(1-\alpha)(\epsilon-1)} \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} \tag{10}$$

Taking into account the relative prices (eq. 9) and labor (eq.10), the relative production of clean inputs compared to dirty in equilibrium is given by:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{\epsilon(1-\alpha)} \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} \tag{11}$$

We can now evaluate the comparative likelihood of successful innovations within both sectors. Using the equation of probability of innovation (eq. 7), substituting relative prices (eq. 9) and labor (eq. 10), we get the relative probability of innovation in terms of productivity and environmental policies.

$$\frac{\eta_{ct}}{\eta_{dt}} = \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} \left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi-1} \tag{12}$$

The probability of innovation is positively influenced by its technological level and negatively by the technological level of the other sector. In the absence of environmental policies, innovation is always greater in the sector with the highest technological level, which typically leads to innovation concentrated in the polluting sector.

Implementing a carbon tax along with a subsidy enhances innovation in the clean sector while lowering it in the dirty sector. From equation 12, I can establish that the tax required to shift innovation towards the clean sector must meet the following condition:

$$\tau > \frac{\left(\frac{A_{dt}}{A_{ct}}\right)^{\frac{\varphi-1}{\epsilon}} - 1}{1 + \phi\left(\frac{A_{dt}}{A_{ct}}\right)^{\frac{\varphi-1}{\epsilon}}} \tag{13}$$

Equation 13 indicates that the greater the technological gap between the clean and dirty sectors, the larger the subsidy required to redirect resources to the clean sector. Furthermore, the subsidy reduces the necessary tax rate, meaning a lower tax is sufficient to reorient innovation. This lower tax accelerates the technological advancement of the clean sector relative to the dirty sector.

Reallocation of labor strengthens the incentives to innovate in the clean sector while weakening those in the dirty sector. This dynamic fosters faster productivity growth in the clean sector, leading to a gradual reduction in its relative price. As a result, environmental policies increase the share of production of the clean sector while reducing the share of the dirty sector.

Proposition 1: *If* $\epsilon > 1$ *then* $\lim_{\frac{A_{ct}}{A_{dt}} \to \infty} Y_t = Y_{ct}$ *and* $\lim_{\frac{A_{ct}}{A_{dt}} \to 0} Y_t = Y_{dt}$
Proof: *Equations 3 and 11 imply that the final good output can be written in the following forms:*

$$Y_t = Y_{ct}\left(1 + \left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}\left(\frac{A_{dt}}{A_{ct}}\right)^{\varphi}\right)^{\frac{\epsilon}{\epsilon-1}} \text{ and } Y_t = Y_{dt}\left(1 + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}\right)^{\frac{\epsilon}{\epsilon-1}}$$

When the technological level of the clean sector is much higher compared to the dirty sector, the production of the final good uses only clean inputs, and the same occurs in the opposite case.

2.2 Level effect of environmental policy

In this subsection, I extend the model to determine the static effect of environmental policies on aggregate production in the short run. I also examine the heterogeneity according to the relationship between the productivity of the sectors.

2.2.1 Effect on sectoral production

Replacing the prices (eq. A8), and labor (eq. A7), in equation 6, I can get the output of two sectors in terms of productivity for each sector.

$$
\begin{aligned}
Y_{ct} &= \alpha^{\frac{2\alpha}{1-\alpha}} \cdot (1+\tau)^{\epsilon} A_{ct}^{\epsilon(1-\alpha)} \cdot \frac{\left(\frac{A_{ct}^{\varphi}}{(1+\tau)^{(\epsilon-1)}} + \frac{A_{dt}^{\varphi}}{(1-\phi\tau)^{(\epsilon-1)}}\right)^{\frac{\alpha}{\varphi}}}{(1+\tau)^{\epsilon} A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon} A_{dt}^{\varphi}} \\
Y_{dt} &= \alpha^{\frac{2\alpha}{1-\alpha}} \cdot (1-\phi\tau)^{\epsilon} A_{dt}^{\epsilon(1-\alpha)} \cdot \frac{\left(\frac{A_{ct}^{\varphi}}{(1+\tau)^{(\epsilon-1)}} + \frac{A_{dt}^{\varphi}}{(1-\phi\tau)^{(\epsilon-1)}}\right)^{\frac{\alpha}{\varphi}}}{(1+\tau)^{\epsilon} A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon} A_{dt}^{\varphi}}
\end{aligned} \tag{14}
$$

Equation A9 indicate that the tax reduce the production of dirty inputs, while the subsidy increase production of clean. Now, in order to identify the direction and magnitude of the effect of the environmental policy, we derive the production with respect to τ.

$$
\begin{aligned}
\frac{\partial \log(Y_{ct})}{\partial \tau} =& \frac{\epsilon}{1+\tau} - \frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi(1-\phi\tau)^{-\epsilon}}{(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{-(\epsilon-1)}}\right) \\
& - \epsilon\left(\frac{(1+\tau)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi(1-\phi\tau)^{\epsilon-1}}{(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon}}\right)
\end{aligned} \tag{15}
$$

$$
\begin{aligned}
\frac{\partial \log(Y_{dt})}{\partial \tau} =& -\frac{\epsilon\phi}{1-\phi\tau} - \frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi(1-\phi\tau)^{-\epsilon}}{(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{-(\epsilon-1)}}\right) \\
& - \epsilon\left(\frac{(1+\tau)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi(1-\phi\tau)^{\epsilon-1}}{(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon}}\right)
\end{aligned} \tag{16}
$$

From equations 15 and 16:

- The effect of a tax on dirty inputs is greater (more positive or less negative) for the clean sector, i.e., $\frac{\partial \log(Y_{ct})}{\partial \tau} > \frac{\partial \log(Y_{dt})}{\partial \tau}$. In other words, a tax on dirty inputs generates a sectoral redistribution in favor of the clean sector at the expense of the dirty sector.

- For low levels of relative productivity of the clean sector, $\frac{A_{ct}}{A_{dt}}$, an increase in the tax rate results in an increase in the production of clean inputs. Specifically, if $\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} < \phi\left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}$, then $\frac{\partial \log(Y_{ct})}{\partial \tau} > 0$.

- For high levels of relative productivity of the clean sector, an increase in the tax rate leads to a decrease in the production of dirty inputs. Specifically, if $\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} > \phi\left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon}$, then $\frac{\partial \log(Y_{dt})}{\partial\tau} < 0$. Therefore, if fiscal policy is strong enough to generate this transition, it will also have a negative effect on the production of dirty inputs. In particular, if $\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi-1}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} > 1$, then $\frac{\partial \log(Y_{dt})}{\partial\tau} < 0$.

- The second derivative with respect to the relative productivity of the clean sector, $\frac{A_{ct}}{A_{dt}}$, is always negative, and exactly the same for both sectors: $\frac{\partial^2 \log(Y_{jt})}{\partial\tau\partial\frac{A_{ct}}{A_{dt}}} < 0$ for $j = \{d, c\}$.[5] This implies that increasing the relative productivity of the clean sector negatively affects the impact of the tax on output for both sectors.

2.2.2 Effect on aggregate production

From the previous subsection, we know that environmental policy generates a reallocation of labor to the clean sector and a redistribution of inputs in the same direction. Using the production function A9 and equation 3, it is possible to analyze the effect of taxes and subsidies on aggregate income.

$$Y_t = \alpha^{\frac{2\alpha}{1-\alpha}} \cdot \left((1+\tau)^{\epsilon-1}A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon-1}A_{dt}^{\varphi}\right)^{\frac{\epsilon}{\epsilon-1}} \cdot \frac{\left(\frac{A_{ct}^{\varphi}}{(1+\tau)^{(\epsilon-1)}} + \frac{A_{dt}^{\varphi}}{(1-\phi\tau)^{(\epsilon-1)}}\right)^{\frac{\alpha}{\varphi}}}{(1+\tau)^{\epsilon}A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon}A_{dt}^{\varphi}} \tag{17}$$

Taking logs and derivatives, we obtain the effect of the tax on final production, and the implications are presented in Proposition 2.

$$\begin{aligned}\frac{\partial \log(Y_t)}{\partial\tau} =& \frac{\epsilon}{(1+\tau)}\left(\frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi\left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-2}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}} - \frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi\left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon}}\right) \\ &- \frac{\alpha}{(1-\alpha)}\frac{1}{(1+\tau)}\left(\frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} - \phi\left(\frac{1-\phi\tau}{1+\tau}\right)^{-\epsilon}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1-\phi\tau}{1+\tau}\right)^{-(\epsilon-1)}}\right)\end{aligned} \tag{18}$$

Proposition 2: *In the absence of subsidies, a tax on dirty production that ensures the energy transition generates a negative effect on aggregate production,* $\frac{\partial \log(Y_t)}{\partial\tau} < 0$*. However, if* $\epsilon > \frac{\alpha}{1-\alpha}$*,* $\tau < \frac{1-\phi}{\phi}$ *and* $0 < \phi < \frac{1}{3}$ *then this negative impact lessens as the relative productivity of the clean sector increases.*

[5] See the detailed procedure in the appendix A.3

Proof:

Claim 1*: If $\phi = 0$ then $\frac{\partial \log(Y_t)}{\partial \tau} < 0$*

if $\phi = 0$ then

$$\frac{\partial \log(Y_t)}{\partial \tau} = \frac{\epsilon}{(1+\tau)} \left(\frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1}{1+\tau}\right)^{\epsilon-1}} - \frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1}{1+\tau}\right)^{\epsilon}} \right) - \frac{\alpha}{(1-\alpha)} \frac{1}{(1+\tau)} \left(\frac{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}}{\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + \left(\frac{1}{1+\tau}\right)^{-(\epsilon-1)}} \right)$$

Notice that $\left(\frac{1}{1+\tau}\right)^{\epsilon-1} > \left(\frac{1}{1+\tau}\right)^{\epsilon-2}$. Therefore $\frac{\partial \log(Y_t)}{\partial \tau} < 0$.

Claim 2*: If $\tau < \frac{1-\phi}{\phi}$ and $0 < \phi < \frac{1}{3}$ then $\frac{\partial^2 \log(Y_t)}{\partial \tau \partial \left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > 0$*

Following a series of manipulations and simplifications (detailed in the appendix A.4), we arrive at the following inequality:

$$\frac{\partial^2 \log(Y_t)}{\partial \tau \partial \left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > (1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon-1}\epsilon \left(\frac{2\phi\tau + (1+\tau)^{-1} - \phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon-1}\right]^2} \right) - (1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)} \frac{\alpha}{1-\alpha} \left(\frac{(1+\tau)^{-1} - \phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{-(\epsilon-1)}\right]^2} \right)$$

Therefore if $(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)} < (1+\tau)^{(\epsilon-1)}(1-\phi\tau)^{(\epsilon-1)}$, $2\phi\tau + (1+\tau)^{-1} - \phi(1-\phi\tau)^{-1} > 0$ and $(1+\tau)^{-1} - \phi(1-\phi\tau)^{-1} < 0$ then $\frac{\partial^2 \log(Y_t)}{\partial \tau \partial \left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > 0$.

Claim 2.1: If $\tau < \frac{1-\phi}{2\phi}$ or $1 > \tau > \frac{1-\phi}{2\phi}$ and $\phi < \frac{1}{3}$ then $(1+\tau)^{-1} - \phi(1-\phi\tau)^{-1} > 0$, $\frac{1}{1+\tau} - \frac{\phi}{1-\phi\tau} = \frac{1-2\phi\tau-\phi}{(1+\tau)(1-\phi\tau)}$

Therefore,

- If $\tau < \frac{1-\phi}{2\phi}$ then $(1+\tau)^{-1} - \phi(1-\phi\tau)^{-1} > 0$
- If $1 > \tau > \frac{1-\phi}{2\phi}$ and $\phi < \frac{1}{3}$ then $1 - 2\phi\tau - \phi > 0$ and $(1+\tau)^{-1} - \phi(1-\phi\tau)^{-1} > 0$

Claim 2.2: If $\tau < \frac{1-\phi}{\phi}$ *then* $(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)} < (1+\tau)^{(\epsilon-1)}(1-\phi\tau)^{(\epsilon-1)}$

$\tau < \frac{1-\phi}{\phi}$ so $\phi\tau < (1-\phi)$ and $0 < (1-\phi-\phi\tau)$, multiplying both sides by τ, $0 < (\tau-\phi\tau-\phi\tau\tau)$. Adding 1 to both sides, $1 < (1+\tau-\phi\tau-\phi\tau\tau)$. Rearranging, $1 < ((1+\tau)-(1+\tau)\phi\tau)$ and $1 < (1+\tau)(1-\phi\tau)$ Since $\epsilon > 1$, $1 < (1+\tau)^{2(\epsilon-1)}(1-\phi\tau)^{2(\epsilon-1)}$. Multiplying both sides by $(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)}$, $(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)} < (1+\tau)^{(\epsilon-1)}(1-\phi\tau)^{(\epsilon-1)}$ Claim 2 follows directly from claims 2.1 and 2.2.

The results presented in this section suggest that implementing environmental policy may initially generate negative economic impacts. However, the extent of these effects is closely linked to the relative productivity of the clean sector. When combined with subsidies, the imposition of taxes can yield positive outcomes for income levels, with the magnitude of these effects diminishing as the clean sector becomes more productive. This occurs because taxes reduce incentives for innovation within the dirty sector, thereby curbing its growth. Consequently, as the clean sector expands relative to the dirty sector, the overall negative impact of taxes on aggregate growth is mitigated.

2.3 Effect on economic growth

In this section, I analyze the effect of a climate policy on growth. Using the equation 3, it is possible to present the growth rates of the economy as a function of the growth of the two sectors and their relative size:

$$\frac{\Delta Y_t}{Y_t} = \left(\frac{Y_{ct}}{Y_t}\right)^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\Delta Y_{ct}}{Y_{ct}} + \left(\frac{Y_{dt}}{Y_t}\right)^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\Delta Y_{dt}}{Y_{dt}} \tag{19}$$

The effect of a carbon tax and subsidy on the total growth rate can be decomposed into two: (i) the effect on the sectoral distribution of income, $\frac{\partial \frac{Y_{ct}}{Y_t}}{\partial \tau} > 0$ and $\frac{\partial \frac{Y_{dt}}{Y_t}}{\partial \tau} < 0$; (ii) the effect on the growth rate of the two sectors, $\frac{\partial \frac{\Delta Y_{ct}}{Y_t}}{\partial \tau} > 0$ and $\frac{\partial \frac{\Delta Y_{dt}}{Y_t}}{\partial \tau} < 0$. Using equation 19 we can derive the effects of taxes and subsidies on the growth rate of the economy.

2.3.1 Effect on sectoral share of production

First, from (Proposition 1) note that the initial share of the production of each sector relative to the total production can be expressed as follows:

$$\frac{Y_{ct}}{Y_t} = \left[1 + \left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}\left(\frac{A_{dt}}{A_{ct}}\right)^{\varphi}\right]^{\frac{-\epsilon}{\epsilon-1}}$$
$$\frac{Y_{dt}}{Y_t} = \left[1 + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}\right]^{\frac{-\epsilon}{\epsilon-1}} \tag{20}$$

Equation 21 indicates that τ generates a recomposition of the product in favor of the clean sector $\frac{\partial\left(\frac{Y_{ct}}{Y_t}\right)}{\partial\tau} > 0$ and against the dirty sector $\frac{\partial\left(\frac{Y_{dt}}{Y_t}\right)}{\partial\tau} < 0$:

$$\frac{\partial\left(\frac{Y_{ct}}{Y_t}\right)}{\partial\tau} = \epsilon\left[1 + \left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-1}\left(\frac{A_{dt}}{A_{ct}}\right)^{\varphi}\right]^{\frac{-\epsilon}{\epsilon-1}-1}\left(\frac{A_{dt}}{A_{ct}}\right)^{\varphi}\left(\frac{1-\phi\tau}{1+\tau}\right)^{\epsilon-2}\cdot\frac{1+\phi}{(1+\tau)^2}.$$
$$\frac{\partial\left(\frac{Y_{dt}}{Y_t}\right)}{\partial\tau} = -\epsilon\left[1 + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}\right]^{\frac{-\epsilon}{\epsilon-1}-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-2}\cdot\frac{1+\phi}{(1-\phi\tau)^2} \tag{21}$$

2.3.2 Effect on sector growth rate

Using equation (A9) it is possible to derive the growth rate of the two sectors.

$$\frac{\Delta Y_{ct}}{Y_{ct}} = \alpha\left(\frac{A_{ct}^{\varphi}\frac{\Delta A_{ct}}{A_{ct}} + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}A_{dt}^{\varphi}\frac{\Delta A_{dt}}{A_{dt}}}{A_{ct}^{\varphi} + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}A_{dt}^{\varphi}}\right) - \varphi\left(\frac{A_{ct}^{\varphi}\frac{\Delta A_{ct}}{A_{ct}}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} + A_{dt}^{\varphi}\frac{\Delta A_{dt}}{A_{dt}}}{A_{ct}^{\varphi}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} + A_{dt}^{\varphi}}\right) + \epsilon(1-\alpha)\frac{\Delta A_{ct}}{A_{ct}}$$
$$\frac{\Delta Y_{dt}}{Y_{dt}} = \alpha\left(\frac{A_{ct}^{\varphi}\frac{\Delta A_{ct}}{A_{ct}} + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}A_{dt}^{\varphi}\frac{\Delta A_{dt}}{A_{dt}}}{A_{ct}^{\varphi} + \left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon-1}A_{dt}^{\varphi}}\right) - \varphi\left(\frac{A_{ct}^{\varphi}\frac{\Delta A_{ct}}{A_{ct}}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} + A_{dt}^{\varphi}\frac{\Delta A_{dt}}{A_{dt}}}{A_{ct}^{\varphi}\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon} + A_{dt}^{\varphi}}\right) + \epsilon(1-\alpha)\frac{\Delta A_{dt}}{A_{dt}} \tag{22}$$

Therefore, it can be inferred that $\frac{\Delta Y_{ct}}{Y_{ct}} - \frac{\Delta Y_{dt}}{Y_{dt}} = \epsilon(1-\alpha)\gamma(\eta_{ct} - \eta_{dt})$.

Proposition 3: *Environmental policy has a positive effect on the aggregate growth rate if* $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} > 1$ *and* $\varphi > 1$.

Proof:

From equation 11 it follows that if $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} > 1$ then $\frac{Y_{ct}}{Y_{dt}} > 1$. Similarly, from 12 it follows that if $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi-1} > 1$ then $\eta_{ct} > \eta_{dt}$.

Claim 1*:* $\frac{Y_{ct}}{Y_{dt}} > 1$ *and* $\eta_{ct} > \eta_{dt}$

Case 1: If $\frac{A_{ct}}{A_{dt}} > 1$ and $\varphi > 1$ then $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\phi} > 1$ and $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\phi-1} > 1$.

Case 2: If $\frac{A_{ct}}{A_{dt}} < 1$ and $\varphi > 1$ then $\left(\frac{A_{ct}}{A_{dt}}\right)^{\phi-1} > \left(\frac{A_{ct}}{A_{dt}}\right)^{\phi}$ so if $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\phi} > 1$ then $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi-1} > 1$.

Therefore, $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\phi} > 1$ and $\varphi > 1$ imply $Y_t^c > Y_t^d$ and $\eta_{ct} > \eta_{dt}$.

Claim 2: $\frac{\partial\left(\frac{\Delta Y_{ct}}{Y_{ct}}\right)}{\partial\tau} > \frac{\partial\left(\frac{\Delta Y_{dt}}{Y_{dt}}\right)}{\partial\tau}$

From equation 22, $\frac{\Delta Y_{ct}}{Y_{ct}} - \frac{\Delta Y_{dt}}{Y_{dt}} = \epsilon(1-\alpha)\gamma(\eta_{ct}-\eta_{dt})$ so, $\frac{\partial\left(\frac{\Delta Y_{ct}}{Y_{ct}}\right)}{\partial\tau} - \frac{\partial\left(\frac{\Delta Y_{dt}}{Y_{dt}}\right)}{\partial\tau} = \epsilon(1-\alpha)\frac{\partial(\eta_{ct}-\eta_{dt})}{\partial\tau}$ which implies that $\frac{\partial\left(\frac{\Delta Y_{ct}}{Y_{ct}}\right)}{\partial\tau} > \frac{\partial\left(\frac{\Delta Y_{dt}}{Y_{dt}}\right)}{\partial\tau}$.

Claim 3: $\frac{\partial\left(\frac{\Delta Y_t}{Y_t}\right)}{\partial\tau} > \left(\frac{\partial\left(\left(\frac{Y_{ct}}{Y_t}\right)^{\frac{\epsilon-1}{\epsilon}}\right)}{\partial\tau}\varphi\gamma(\eta_{ct}-\eta_{dt})\right) + \left(\frac{Y_{ct}}{Y_t}\right)^{\frac{\epsilon-1}{\epsilon}}\left(\frac{\partial\left(\frac{\Delta Y_{ct}}{Y_{ct}}\right)}{\partial\tau} - \frac{\partial\left(\frac{\Delta Y_{dt}}{Y_{dt}}\right)}{\partial\tau}\right)$ From claims 1, 2 and 3 it follows that if $\left(\frac{1+\tau}{1-\phi\tau}\right)^{\epsilon}\left(\frac{A_{ct}}{A_t^d}\right)^{\phi} > 1$ and $\varphi > 1$, then $\frac{\partial\left(\frac{\Delta Y_t}{Y_t}\right)}{\partial\tau} > 0$ and $\frac{\partial\left(\frac{\Delta Y_t}{Y_t}\right)}{\partial\tau} > 0$.

Corollary: The impact of a carbon tax on the growth rate is not always negative; it depends on two key factors: (i) the initial share of the clean sector in total production, and (ii) the relative productivity of this sector. As the productivity of the clean sector increases, environmental policies can have a positive effect on overall economic growth, shifting the balance toward a more sustainable growth trajectory.

To provide a quantitative understanding of the implications of the energy mix, we report the results of a parameter calibration using different initial values of clean and dirty goods production. This exercise highlights the effect of a tax on different rates of production of clean and dirty inputs in their initial state. We use the parameters Acemoglu *et al.* (2012a), where $\gamma = 2$, $\alpha = 0.3$, and $\epsilon = 3$, and we only considered a period, that is, period $t+1$, after one year of implementation of a carbon tax.

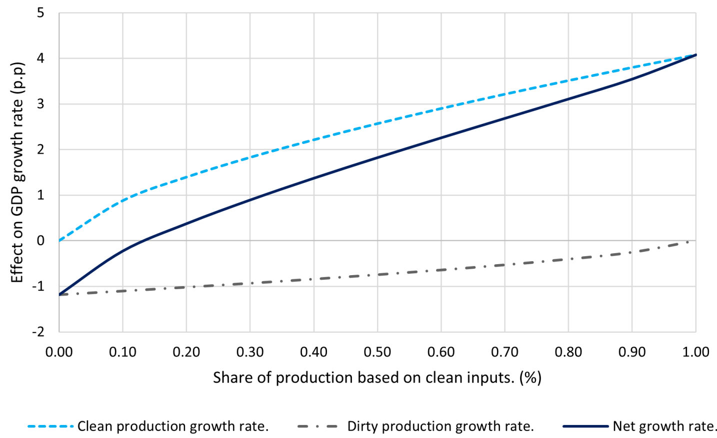


Figure 1: Representation of the effect of the carbon tax on the growth rate (g_t/τ).

In summary, a fiscal policy that combines taxes and subsidies to steer the economy towards a productive transformation aimed at decarbonization impacts both the income level and the growth rate. The effect on income levels tends to be negative, though less pronounced for economies with a cleaner energy mix. Conversely, the effect on the growth rate is positive, as environmental policy stimulates the expansion of the sector with the highest contribution to output. In the following section, we test the key implications of the theoretical model: (i) The negative impact of a carbon tax is more pronounced for economies with a dirtier energy matrix, (ii) the adverse effect of the carbon tax diminishes over time as the economy undergoes decarbonization, and for economies with a cleaner energy mix, environmental policy ultimately accelerates growth.

3 Data and Empirical Strategy

3.1 Data

To empirically analyze the relation of a carbon tax on income and GDP growth, we use data from the World Bank Group, Energy Consumption data are from the International Energy Agency, Carbon pricing data are from World Carbon Pricing Database.

I use a yearly data panel from a sample of 66 countries, of which 23 had implemented a carbon tax. The sample covers the period from 1990 to 2020. Table 1 presents descriptive statistics of the variables of interest and the sources of the databases. The outcome variables studied are GDP growth (%) and the employment rate measured as the number of employees over an economically active population (%). Table 2 in the annex presents in detail the characteristics of the carbon tax for each of the countries studied. It can be seen that since 2010 the adoption of carbon taxes in the countries has increased. The table also shows the carbon tax's monetary value as well as the percentage of emissions covered by the tax.

Table 1: Description of the main outcome variables.

Variable	**Mean**	**Median**	**Std. Dev.**	**Source**
Real GDP (millions US$ constant 2017)	1026887	258975	2511953	Penn World Table
Crecimiento del PIB (anual %)	2.86%	2.99%	4.33%	Data WorldBank
GDP per capita (current US$)	9.384	9.532	1.143	Data WorldBank
Employment rate (% total labor)	92.30%	92.94%	4.56%	Data WorldBank
Population, total	49035868	9771437	165987702	Data WorldBank
Primary energy consumption (TWh)	1589	324	4390	Our World in Data
Clean energy fraction* (% total consumption)	14%	9%	16%	International Energy Agency
Clean electricity fraction* (% total consumption)	37%	32%	31%	International Energy Agency
Countries	66			
Observations	2044			

**Primary sources of clean energy are hydro, nuclear, solar, and wind power.*

To apply the theoretical model to real-world data, I use the share of primary energy consumed by each source as a proxy for the initial rates of production of clean and dirty inputs, Y_c and Y_d. I categorized the sample of countries based on the share of primary energy consumed by each source, dividing them into those with a low-carbon intensity energy mix and those with a high-carbon intensity energy mix. The term “low-carbon intensity” is used to describe the energy consumption of hydro, nuclear, solar, and wind sources. These sources emit lower levels of carbon than traditional fossil fuels. Conversely, the term “high-carbon intensity” is used to describe energy generated from the combustion of fossil fuels, such as coal, oil, natural gas, and biofuels. Figure 2 shows the share of energy from low-carbon intensity sources by countries.

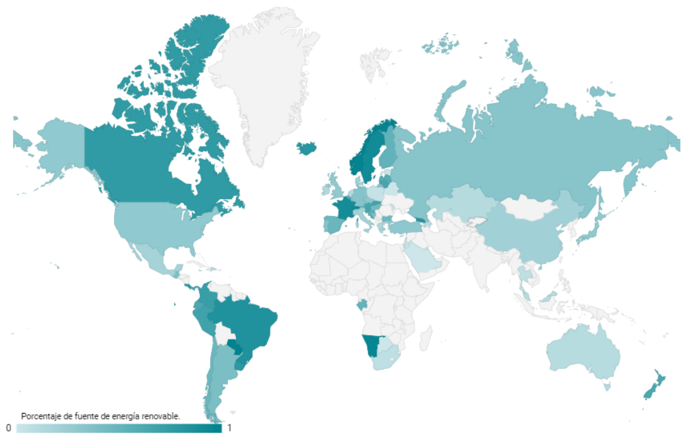


Figure 2: Map of countries according to the share of clean energy sources

The countries with a share of clean energy higher than average (14%), at the time of implementation of the carbon tax, constitute the database of countries with a “low-carbon intensity” energy matrix. Similarly, the countries that had a clean energy share lower than average (14%) at the time of implementing the carbon tax constitute the database of countries with a “high-carbon intensity” energy matrix. Table 3 presents the statistics of the outcome variables for each sample, the full sample of 66 countries, and the sample of countries with polluting and clean energy mix.

The graph 3 shows the relationship between the share of clean energy in the energy mix and GDP growth in countries with and without a carbon tax. The relationship has a slight negative slope, indicating that countries with a higher share of clean energy have slightly lower GDP growth rates. It is important to note, however, that this does not imply that countries with carbon taxes have the lowest growth rates.

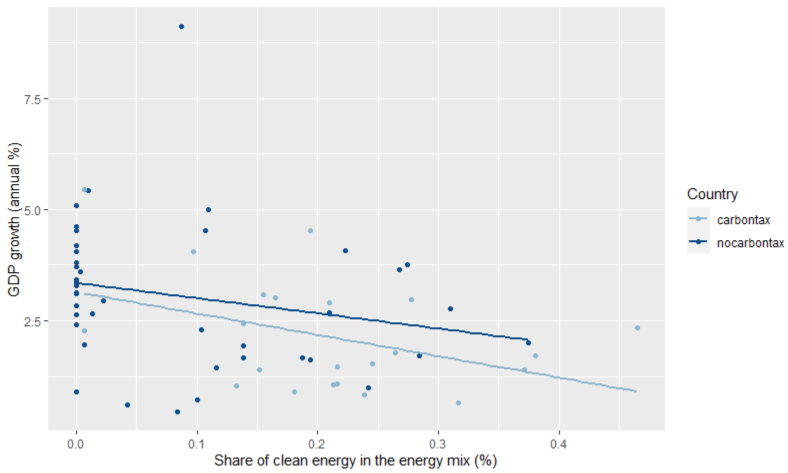


Figure 3: The relationship between GDP growth and the proportion of clean energy sources in the energy mix

3.2 Empirical strategies

This paper estimates the impact of a carbon tax on income and growth, differentiated by primary energy sources, to empirically validate the theoretical model's propositions. Following Känzig & Konradt (2023) and Metcalf & Stock (2023), I apply the Local Projections (LP) method (Jordà, 2005) to identify the causal and dynamic effects of carbon taxes on economic growth, allowing us to assess how unexpected tax shocks affect these variables over time. Local Projection works by running a sequence of separate regressions for each time horizon after the carbon policy shock (e.g., the effect of a carbon tax in year 1, year 2, etc.). For each horizon, we project the outcome of interest (e.g., GDP) as a function of past variables, including the shock, to trace out its dynamic impact over time.

As discussed in Metcalf & Stock (2023), carbon prices can be decomposed into two components: one determined by historical economic and financial factors, and the other orthogonal to the economy. The latter may include shifts in political preferences for environmental policies, international climate commitments, or legislated tax schedules. By controlling for past economic developments, we aim to isolate variation in carbon prices that can be considered exogenous, as a carbon policy shock. This allows for the estimation of dynamic causal effects through local projections, incorporating relevant economic controls. LP estimates the effect of a shock directly at each horizon of interest using straightforward regressions. This makes LP simpler, more flexible, and robust to misspecification compared to VAR models.

The main assumptions for estimating the causal effect are: (i) changes in the carbon tax must not be anticipated by previous economic growth or international economic shocks; and (ii) the effect of carbon taxes unfolds over time, with Local Projection model capturing this dynamic behavior. These models provide estimates of both short- and long-term impacts. LP on the long-difference measures the cumulative of the per-period percentage changes helping to evaluate the overall effect of the treatment plan. By including fixed effects by country and year, the models ensure that variations in economic growth attributable to global or shared economic factors do not confound the estimates of the carbon tax's impact on growth.

Using the LP approach, the package R "lpirfs" (Adämmer, 2019), the aim of this study is to estimate the effect of the carbon tax on (i) the primary consumption of clean and fossil energy sources (energy transition); (ii) the GDP growth rates that support Proposition 3 of the theoretical model; and (iii) the income levels that validate Proposition 2. In all specifications, as done in the literature, we include carbon prices in real terms, adjusted for coverage by deflating them and weighting based on the country-specific carbon tax emission coverage.

3.2.1 Effect of a climate policy on energy transition.

To analyze the channels through which the carbon tax affects energy prices, the energy mix, carbon intensity (kgCO2/USD PPP 2015), and energy intensity (MJ/USD PPP 2015), we employ the following econometric specification. I include a control variable, a dummy indicating whether the country has an additional carbon policy, such as an ETS, in year t. Additionally, we control for time-invariant country-specific characteristics using country fixed effects and account for groups of countries, like the European Union, or global controls that might explain differential characteristics between subsets of countries, as represented in the following equation:

$$y_{i,t+h} - y_{i,t-1} = \Phi_i^h + \Phi_t^h + \beta^h \tau_{i,t} + \sum_{j=1}^{p} \theta_i^h \Delta y_{i,t-p} + \epsilon_{i,t+h} \tag{23}$$

where $y_{i,t}$ is the outcome variable of interest in country i at time $t+h$ and β_h measures the dynamic effect of an unexpected change in the carbon tax at horizon h. We control for p lags of the outcome variable to ensure that the estimation isolates the effect of the carbon tax shock from the influence of past dynamics. Essentially, the lags account for persistence in the dependent variable, enabling the LP method to produce more reliable estimates of the dynamic effects of the shock.

3.2.2 Effect of a carbon tax on income level by type of energy source (Proposition 2).

We can evaluate Proposition 2 which states that the effect of a carbon tax is an increasing function on the share of clean energy mix using the local projection method. For that purpose, we include an interaction term in our local projections:

$$Y_{i,t+h} - Y_{i,t-1} = \Phi_i^h + \Phi_t^h + \beta^h \tau_{i,t} + \gamma^h \tau_{i,t} \times X_{t_0-1} + \sum_{j=1}^{p} \theta_i^h \Delta Y_{i,t-p} + \epsilon_{i,t+h} \tag{24}$$

where $Y_{c,t}$ is the log(GDP), γ^h captures the differences in the response to carbon policy shocks depending on the share of renewable energy in the energy mix.

When the outcome variable is the GDP growth rate this estimator tests the *proposition 2.* Also include α_c country fixed effects c for unobserved country-specific characteristics and Φ_t time fixed effects to capture other policy and time-varying resource price shocks, among other changes that may occur over time.

3.2.3 Effect of a carbon tax on growth by type of energy source (Proposition 3).

$$Growth_{i,t+h} - Growth_{i,t-1} = \Phi_i^h + \Phi_t^h + \beta^h \tau_{i,t} + \gamma^h \tau_{i,t} \times X_{t_0-1} + \sum_{j=1}^{p} \theta_i^h \Delta Growth_{i,t-p} + \epsilon_{i,t+h} \tag{25}$$

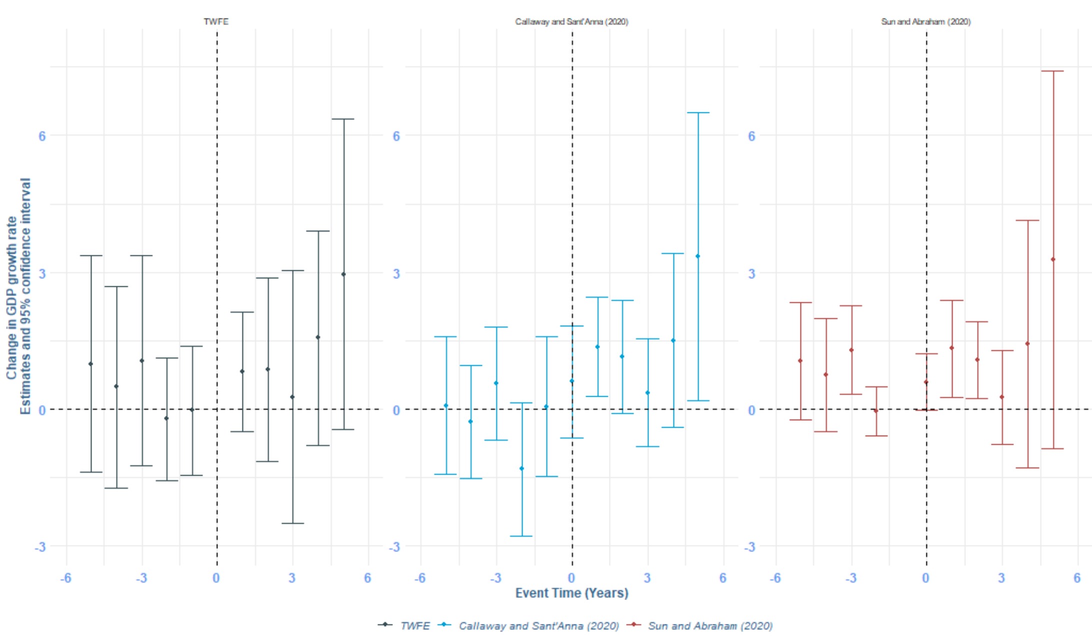
where $\frac{\Delta Y_{i,t}}{Y_{i,t}}$ is the growth rate, and γ^h is the effect of an unexpected change in the carbon tax interacted with the variable of share of renewable energy rate at time t on annual GDP growth h periods hence.

4 Results

4.1 Implications of carbon tax on growth rate and employment

Figure 4 presents the effect of implementing a carbon tax on the annual GDP growth rate using the database of 66 countries. Implementing a carbon tax is associated with an increase in the GDP growth rate in the early years of the climate policy, and is maintained when using different model specifications. Table 4 presents the estimators of the average effect of implementing a carbon tax on GDP growth over the next ten years. It is observed that implementing the carbon tax is associated with a 1.5 percentage point growth in GDP one year after the policy, this effect is significant using the Sun et al. specification (Column 3). Using the TWFE and Callaway specification, implementing the carbon tax is associated with 0.9 and 0.6 percentage point growth in GDP, respectively, in the year after adopting the policy. The effect under the Callaway methodology is consistent with the results from the literature in which the effect of the carbon tax between the first and second year is associated with an increase in the GDP growth rate of 0.5 percentage points, in the literature implementing a carbon tax is not associated with adverse effects on the GDP growth rate.

Figure 4: Implications of carbon tax on GDP growth rate.



This result implies that if a country hypothetically implements a carbon tax it can be expected to, on average, experience an increase in the growth rate of 1 percentage point in the following year after implementing the policy.

4.2 Heterogeneous effects according to the composition of the energy matrix

In this section, I empirically estimate how the effect of introducing a carbon tax on the GDP growth rate and the employment rate varies according to the composition of the countries' energy matrix, i.e., according to the share of primary energy sources in final consumption. To test the corollaries derived from the theoretical model I use the share of energy consumed from clean and polluting sources as a proxy for the initial share of the clean and polluting sectors in the final product.

4.2.1 A carbon tax in polluting countries.

To test Corollary 1, it would be expected that using the sample of polluting countries (whose consumption of energy from fossil and biofuel sources is higher than the sample average), the effect of introducing a carbon tax on the annual GDP growth rate may be negative.

Figure 5: Annual GDP growth (%) in countries with a polluting energy matrix.

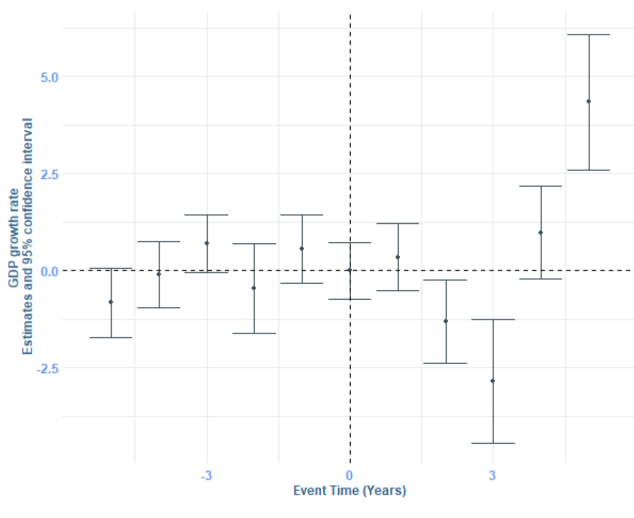


Figure 5 presents the coefficients of the average cumulative effect of the carbon tax on the growth rate in polluting countries, and on the y-axis, in addition to indicating the magnitude, the 95% confidence intervals are presented. It is observed that implementing the carbon tax in countries with a polluting energy matrix is associated with a reduction in the growth rate in the second and third years the In the second year the cumulative effect of implementing the carbon tax is -1.3 percentage points of annual GDP, in the third year the effect is -2.8 percentage points. This effect can be explained by the cost of discouraging the innovation of technologies that require polluting energy. In the long term, a positive effect on the annual GDP growth rate may be due to countries adopting new clean technologies.

4.2.2 A carbon tax in clean countries.

Corollary 1 implies that introducing a carbon tax favors the annual GDP growth rate in countries with a cleaner-than-average energy matrix.

The effects reported in table 5 show the estimators for countries with a clean and polluting energy matrix, columns 2 and 4 respectively. The results suggest that if hypothetically a country with a clean energy matrix implements a carbon tax it can be expected to experience an increase in the growth rate of 1.8 percentage points in the following year after implementing the policy. This result validates the stipulation in Corollary 1 that the higher the initial share of the clean sector in final production, the greater the positive effect of the carbon tax. In this case, I approximate the clean sector's share of final energy consumption to the share of clean primary energy sources.

Figure 6: GDP growth (%) in countries with clean energy matrix.

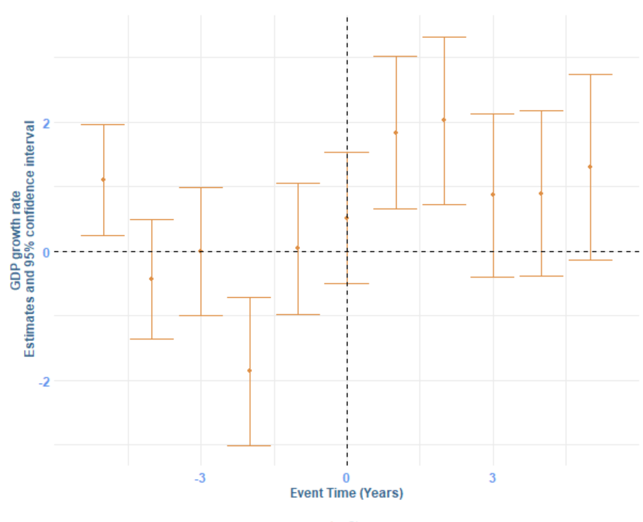


Figure 6 shows that the effect of a carbon tax on the GDP growth rate is positive for countries whose primary energy comes from clean sources. This result suggests that introducing a carbon tax is associated with an increase in annual GDP of 1.4 percentage points in the first 5 years after implementing the policy, this effect is significant. The result suggests that the higher the share of clean sources at the time of implementing the climate policy, the effect of the tax on the GDP growth rate will be favorable.

5 Robustness exercises

To verify whether the previous results were robust, I performed several econometric exercises. First, I estimated the effect of the carbon tax on GDP using different samples of polluting and clean countries, based on the thresholds of the share of energy sources. Second, I used the sources of electricity generation, in exchange for the energy matrix, as they can approximate the share of the sectors (clean and polluting) in the final production. Third, I estimate the effect of the tax using two samples of countries based on the magnitude of the carbon tax in 2020 and the proportion of emissions covered by the tax.

5.1 Exercise with Various Samples

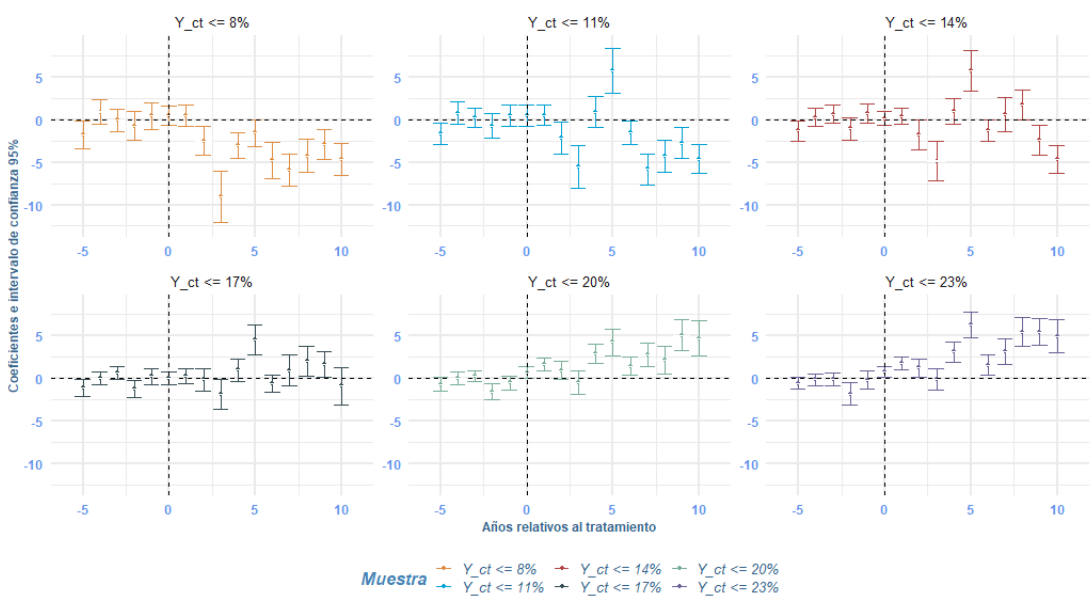


Figure 7: Effect of the carbon tax at different thresholds of the participation of energy sources.

I assess the impact of the carbon tax on growth rates by examining different samples of polluting and clean countries. The goal is to identify the threshold at which the carbon tax's effect shifts from negative (for polluting countries) to positive. I defined various cut-off points Θ based on the proportion of clean energy sources in the total energy consumption. Specifically, I considered scenarios where the sample of polluting countries does not exceed certain percentages of clean energy sources. The findings on the carbon tax's impact on GDP growth, relative to these cut-off points for clean and polluting samples, are presented in 7. When the sample of polluting countries includes less than 8% clean energy (representing the most polluting countries), the effect is highly negative. Conversely, when the sample reaches 23% clean energy, the effect becomes positive. The carbon tax is beneficial for GDP growth in countries with an energy matrix comprising at least 17% clean energy.

5.2 Effect using electricity mix

The electricity mix is composed of the set of sources available to generate the electricity consumed within a country. Electricity unlike energy can be generated entirely by renewable sources, therefore, for this exercise, I divide the sample of polluting and clean countries based on the 37% share of clean sources. That is, if the country generates more than 37% of electricity from sources such as solar, wind, hydro, and nuclear, it is considered clean, and would be part of the sub-sample of clean countries, otherwise it would belong to the sub-sample of polluting countries.

Figure 8: Effect of carbon tax on GDP growth rate in countries with polluting electricity mix.

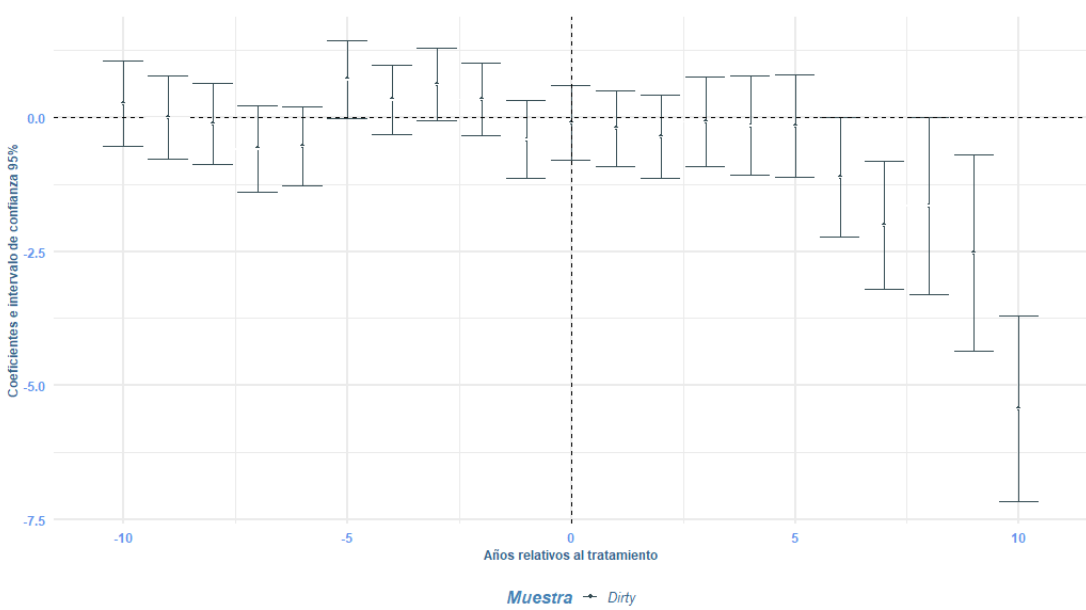
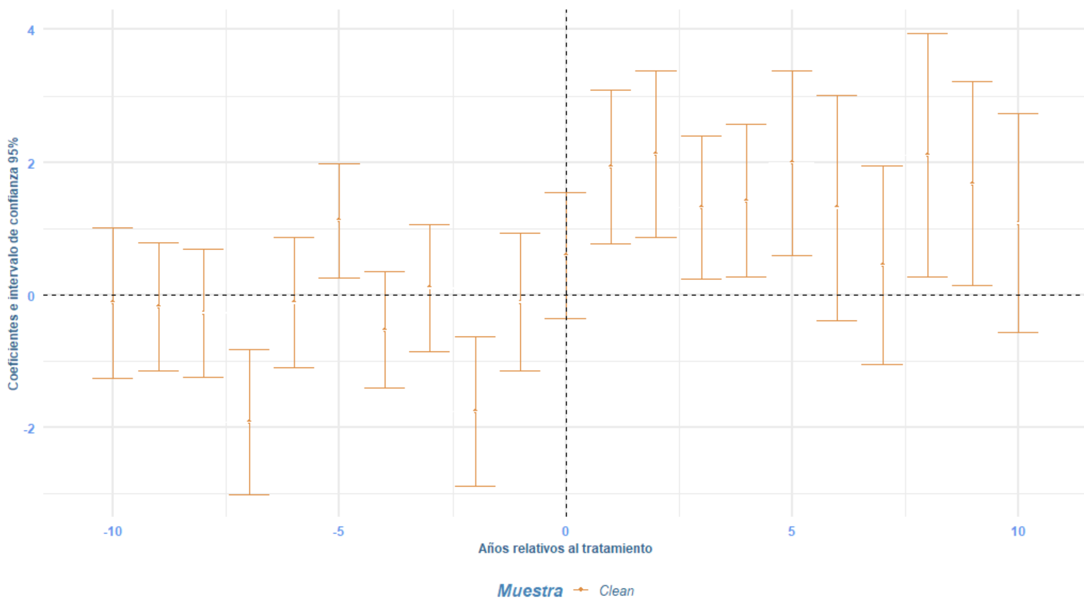


Table 8 presents the estimators of the effect of the carbon tax on the GDP growth rate according to the electricity matrix. The coefficients estimated with the electricity matrix are similar in magnitude and direction to those estimated with the energy matrix, however, these results are significant in more periods unlike those estimated with the energy matrix. Figure 8 presents the coefficients of the effect of the carbon tax on the growth rate using the sample of countries with a polluting electricity matrix. The carbon tax is associated with negative growth rates, this effect is larger in magnitude than the one calculated with the sample of countries divided according to the energy matrix. On the other hand, the figure 9 shows similar results to those obtained with the sample of clean countries using the energy matrix. For countries with a clean electricity matrix, the effect is slightly positive, increasing the growth rate by 0.6 percentage points in the first 5 years after implementing the climate policy.

Figure 9: Effect of carbon tax on GDP growth rate in countries with clean electricity mix.



6 Conclusions

This study provides robust evidence that the macroeconomic impact of a carbon tax is significantly influenced by the composition of a country's energy mix. By examining the proportion of energy generated from fossil fuels and low-carbon-intensity sources, we highlight the heterogeneity in outcomes following the implementation of a carbon tax. In economies heavily reliant on fossil fuels, the introduction of a carbon tax may lead to a short-term decline in GDP growth, as predicted by the theoretical model. However, the long-term trajectory suggests that growth can recover, particularly as the share of clean energy increases or energy efficiency improves, validating proposition 1 of the model.

Conversely, in countries where energy production relies primarily on low-carbon sources, the imposition of a carbon tax may positively impact GDP growth in the short term, with minimal or no negative effects on employment. This suggests that countries with cleaner energy mixes are better positioned to absorb the initial economic costs of carbon pricing and can even experience economic benefits from the transition to cleaner production.

Our findings also indicate that the adverse effects on GDP growth in high-carbon-intensity economies tend to dissipate over time. This is due to a shift in demand away from polluting goods, which incentivizes innovation and expansion in the clean energy sector. As this sector grows, it eventually overtakes the polluting industries, allowing the economy to return to its pre-tax growth trajectory. The transition is marked by a reallocation of labor and capital towards cleaner technologies, driven by the carbon tax's effect of increasing the relative cost of polluting goods.

The study also supports the idea that a carbon tax can serve as an effective policy tool not only for reducing carbon emissions but also for fostering long-term clean economic growth. As the tax increases the costs of production in high-emission sectors, it simultaneously encourages greater productivity and innovation in the clean sector, ultimately transforming the economic structure towards sustainability.

A key policy implication derived from our model is the strategic use of carbon tax revenues. In the early stages of the transition, it is crucial to reinvest these revenues in the development and scaling of clean technologies, enabling the clean energy sector to meet growing demand. This reinvestment can mitigate the short-term negative impact on economic growth, facilitating a smoother transition to a low-carbon economy.

In conclusion, the study underscores the importance of considering a country's energy mix when designing carbon taxes and other climate policies. Tailoring these policies to national contexts can optimize their economic and environmental effectiveness, minimizing transitional costs while accelerating the shift towards sustainable development.

A Appendix

A.1 Intermediate Inputs

From the first-order conditions is obtained the demand for machines and labor in each sector,

$$x_{jit} = \left(\frac{\alpha P_{jt}}{p_{jit}}\right)^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \quad \text{and} \quad L_{jt} = \left(\frac{(1-\alpha)P_{jt}}{w_{jt}}\right)^{\frac{1}{\alpha}} A_{jit}^{\frac{1-\alpha}{\alpha}} x_{jit} \tag{A1}$$

where w_{jt} denotes the wage paid for each unit of labor hired and p_{jit} is the price that the producer of inputs must pay for each machine used.

Producers of intermediate goods maximize profits by knowing the demand function they face,

$$\max_{x_{ji}} \{p_{jit} x_{jit} - x_{jit}\} \tag{A2}$$

Machines are produced at marginal cost ν under monopolistic competition and, sold at price p_{jt}, taking into account the demand for machines x_{jit} in the sector in which they are used. Therefore the profits of the monopolists, π_{jt}, are given by: $\pi_{jt} = (p_{jit} - \nu)x_{jit}$. So, replacing the demand for machines, the profits of the monopolist are:

$$\pi_{jt} = (p_{jit} - \nu)\left(\frac{\alpha P_{jt}}{p_{jit}}\right)^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \tag{A3}$$

Following Acemoglu *et al.* (2012a), we normalize $\nu = \alpha^2$, so, each monopolist sets a price $p_{jit} = \frac{1}{\alpha}$. Thus, replacing the price of machine $p_{jit} = \frac{1}{\alpha}$ in equation A1, the optimal demand for machines and the profits of intermediate goods in each sector can be written as:

$$x_{jit} = \alpha^{\frac{2}{1-\alpha}} A_{jit} L_{jt} \left(P_{jt}\right)^{\frac{1}{1-\alpha}} \quad \text{and} \quad \pi_{jt} = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} P_{jt}^{\frac{1}{1-\alpha}} A_{jit-1} L_{jt} \tag{A4}$$

and the quantities of inputs produced in sector j are:

$$Y_{jt} = \alpha^{\frac{2\alpha}{1-\alpha}} A_{jt} L_{jt} \left(P_{jt}\right)^{\frac{\alpha}{1-\alpha}} \tag{A5}$$

Combining this equation A3 and replacing ν, the equilibrium profits of machine producers can be written as:

$$\pi_{jt} = (1-\alpha)\alpha^{\frac{1+\alpha}{1-\alpha}} P_{jt}^{\frac{1}{1-\alpha}} A_{jit-1} L_{jt} \tag{A6}$$

A.2 Factors of production in equilibrium

From the profit-maximization problem of the producer of machines, assuming the total labor supply is normalized to one, such that $L_{ct} + L_{dt} = 1$, and given that equilibrium wages are equal, $w_{ct} = w_{dt}$, we can substitute the price index (equation 4) to express the equilibrium labor allocation in each sector as follows:

$$\begin{aligned} L_{ct} &= \frac{(1+\tau)^{\epsilon} A_{ct}^{\varphi}}{(1-\tau\phi)^{\epsilon} A_{ct}^{\varphi} + (1+\tau)^{\epsilon} A_{dt}^{\varphi}} \\ L_{dt} &= \frac{(1-\tau\phi)^{\epsilon} A_{dt}^{\varphi}}{(1-\tau\phi)^{\epsilon} A_{ct}^{\varphi} + (1+\tau)^{\epsilon} A_{dt}^{\varphi}} \end{aligned} \tag{A7}$$

where $\varphi = (\epsilon - 1)(1-\alpha)$. Additionally, the equilibrium prices can be determined as follows:

$$\begin{aligned} P_{ct} &= \frac{\left((1+\tau)^{-(\epsilon-1)} A_{ct}^{\varphi} + (1-\tau\phi)^{-(\epsilon-1)} A_{dt}^{\varphi}\right)^{\frac{1}{\epsilon-1}}}{A_{ct}^{(1-\alpha)}} \\ P_{dt} &= \frac{\left((1+\tau)^{-(\epsilon-1)} A_{ct}^{\varphi} + (1-\tau\phi)^{-(\epsilon-1)} A_{dt}^{\varphi}\right)^{\frac{1}{\epsilon-1}}}{A_{dt}^{(1-\alpha)}} \end{aligned} \tag{A8}$$

It is important to note that subsidies for clean production increase the prices of both inputs, while taxes on dirty production decrease them. However, because the percentage change is proportional for both prices, the relative price ratio remains unchanged. Regarding labor equilibrium, higher productivity and the carbon tax in the clean sector lead to a greater allocation of labor to that sector. Furthermore, as the clean energy subsidy increases, the labor share in the clean sector expands, even if the technological level in the clean sector is relatively low.

Replacing the prices (eq. A7), and labor (eq. A8), in equation 6, I can get the output of two sectors in terms of productivity for each sector.

$$\begin{aligned} Y_{ct} &= \alpha^{\frac{2\alpha}{1-\alpha}} \cdot (1+\tau)^{\epsilon} A_{ct}^{\epsilon(1-\alpha)} \cdot \frac{\left(\frac{A_{ct}^{\varphi}}{(1+\tau)^{(\epsilon-1)}} + \frac{A_{dt}^{\varphi}}{(1-\phi\tau)^{(\epsilon-1)}}\right)^{\frac{\alpha}{\varphi}}}{(1+\tau)^{\epsilon} A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon} A_{dt}^{\varphi}} \\ Y_{dt} &= \alpha^{\frac{2\alpha}{1-\alpha}} \cdot (1-\phi\tau)^{\epsilon} A_{dt}^{\epsilon(1-\alpha)} \cdot \frac{\left(\frac{A_{ct}^{\varphi}}{(1+\tau)^{(\epsilon-1)}} + \frac{A_{dt}^{\varphi}}{(1-\phi\tau)^{(\epsilon-1)}}\right)^{\frac{\alpha}{\varphi}}}{(1+\tau)^{\epsilon} A_{ct}^{\varphi} + (1-\phi\tau)^{\epsilon} A_{dt}^{\varphi}} \end{aligned} \tag{A9}$$

A.3 Second derivative of the effect of the tax and relative productivities on sectoral production

$$
\begin{aligned}
\frac{\partial \log(Y_{ct})}{\partial \tau} =& \frac{1}{1+\tau}\left[\left(\frac{\epsilon}{(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right) - \frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{1-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}}{(1+\tau)^{1-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right)\right] \\
&+\phi\left[\left(\frac{\epsilon(1-\phi\tau)^{-\epsilon}}{(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right) + \frac{\alpha}{1-\alpha}\frac{(1-\phi\tau)^{\epsilon-1}}{(1+\tau)^{1-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right]
\end{aligned}
\tag{A10}
$$

so If $\phi = 0$ then

$$
\frac{\partial \log(Y_{ct})}{\partial \tau} = \frac{1}{1+\tau}\left[\left(\frac{\epsilon}{(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right) - \frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{1-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}}{(1+\tau)^{1-\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+1}\right)\right]
\tag{A11}
$$

The second derivative with respect to the relative productivity of the clan sector $\frac{A_{ct}}{A_{dt}}$ is always negative and exactly the same, for both sectors Y_{ct} and Y_{dt}.

$$
\begin{aligned}
\frac{\partial^2 \log(Y_{jt})}{\partial\tau\partial\frac{A_{ct}}{A_{dt}}} =& -\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-\epsilon}(1-\phi\tau)^{-(\epsilon-1)} + (1+\tau)^{-(\epsilon-1)}\phi(1-\phi\tau)^{-\epsilon}}{\left((1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{-(\epsilon-1)}\right)^2}\right) \\
&-\epsilon\left(\frac{(1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon} + (1+\tau)^{\epsilon}\phi(1-\phi\tau)^{\epsilon-1}}{\left((1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon}\right)^2}\right)
\end{aligned}
\tag{A12}
$$

A.4 Second derivative of the effect of the tax and relative productivities on final good production

The analysis of the second derivative with respect to the relative productivity of the clean sector allows us to prove the second part of Proposition 2.

$$
\begin{aligned}
\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} =& \epsilon\left(\frac{(1+\tau)^{\epsilon-2}(1-\phi\tau)^{\epsilon-1} - (1+\tau)^{\epsilon-1}\phi(1-\phi\tau)^{\epsilon-2}}{\left[(1+\tau)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon-1}\right]^2}\right) \\
&-\epsilon\left(\frac{(1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon} - (1+\tau)^{\epsilon}\phi(1-\phi\tau)^{\epsilon-1}}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{\epsilon}\right]^2}\right) \\
&-\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-\epsilon}(1-\phi\tau)^{-(\epsilon-1)} - (1+\tau)^{-(\epsilon-1)}\phi(1-\phi\tau)^{-\epsilon}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi} + (1-\phi\tau)^{-(\epsilon-1)}\right]^2}\right)
\end{aligned}
$$

$$\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} = (1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon-1}\epsilon\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon-1}\right]^2}\right)$$
$$-(1-\phi\tau)^{\epsilon-1}(1+\tau)^{\epsilon-1}\epsilon\left(\frac{(1-\phi\tau)-(1+\tau)\phi}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon}\right]^2}\right)$$
$$-(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)}\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{-(\epsilon-1)}\right]^2}\right)$$

$$\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} = (1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon-1}\epsilon\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{\epsilon-1}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon-1}\right]^2}\right)$$
$$+(1-\phi\tau)^{\epsilon-1}(1+\tau)^{\epsilon-1}\epsilon\left(\frac{2\phi\tau}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon}\right]^2}\right)$$
$$-(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)}\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{-(\epsilon-1)}\right]^2}\right)$$

Therefore, (i) $\lim_{\frac{A_{ct}}{A_{dt}}\to\infty}\frac{\partial^2\log(Y_t)}{\partial\tau\partial\frac{A_{ct}}{A_{dt}}^{\varphi}}=0$ (ii) If $\epsilon>\frac{\alpha}{1-\alpha}$, $\frac{1-\phi}{\phi}>\tau$ and $\frac{(1-\phi\tau)^{-(\epsilon-1)}-(1-\phi\tau)^{\epsilon-1}}{(1+\tau)^{\epsilon-1}-(1+\tau)^{1-\epsilon}}>(\frac{A_{ct}}{A_{dt}})^{\varphi}$ then $\frac{\partial^2\log(Y_t)}{\partial\tau\partial\frac{A_{ct}}{A_{dt}}^{\varphi}}>0$ Now, given that $(1+\tau)>1$ and $(1-\phi\tau)<1$

$$\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > (1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon-1}\epsilon\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon-1}\right]^2}\right)$$
$$+(1-\phi\tau)^{\epsilon-1}(1+\tau)^{\epsilon-1}\epsilon\left(\frac{2\phi\tau}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon-1}\right]^2}\right)$$
$$-(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)}\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{-(\epsilon-1)}\right]^2}\right)$$

so

$$
\begin{aligned}
\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} >& (1+\tau)^{\epsilon-1}(1-\phi\tau)^{\epsilon-1}\epsilon\left(\frac{2\phi\tau+(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{\epsilon}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{\epsilon-1}\right]^2}\right) \\
&-(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)}\frac{\alpha}{1-\alpha}\left(\frac{(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1}}{\left[(1+\tau)^{-(\epsilon-1)}\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}+(1-\phi\tau)^{-(\epsilon-1)}\right]^2}\right)
\end{aligned}
$$

Therefore if $(1+\tau)^{-(\epsilon-1)}(1-\phi\tau)^{-(\epsilon-1)} < (1+\tau)^{(\epsilon-1)}(1-\phi\tau)^{(\epsilon-1)}$, $2\phi\tau+(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1} > 0$ and $(1+\tau)^{-1}-\phi(1-\phi\tau)^{-1} < 0$ then $\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > 0$ then $\frac{\partial^2 \log(Y_t)}{\partial\tau\partial\left(\frac{A_{ct}}{A_{dt}}\right)^{\varphi}} > 0$

Table 2: Characteristics of the carbon tax in the countries analyzed.

Jurisdictions	**Sectors covered**	**Fossil fuels covered**	**Point of Taxation**	**Year**	**GHG emissions**	**GHG covered**	**Price**
Argentina	All sectors with some exemptions.	Liquid and gaseous fossil fuels	Producers, distributors and importers.	2018	441 MtCO2e	20%	US$6/tCO2e
Canada	All sectors with some exemptions.	Fossil fuels	Registered distributors of the fossil fuels.	2019	817 MtCO2e	22%	US$32/Tco2
Chile	Power and industry sectors.	Fossil fuels	Users of the fossil fuels.	2017	149 MtCO2e	39%	US$5/tCO2e
Colombia	All sectors with some exemptions.	Liquid and gaseous fossil fuels	Sellers and importers of the fossil fuels.	2017	190 MtCO2e	24%	US$5/tCO2e
Denmark	Buildings and transport, exempt sectors covered by ETS.	Fossil fuels	Distributors and importers.	1992	63 MtCO2e	35%	US$28/tCO2e
Estonia	Power and industry sectors.	Fossil fuels used for thermal energy	Users of the fossil fuels.	2000	28 MtCO2e	6%	US$2/tCO2e
Finland	Industry, transport, and buildings sectors.	Fossil fuels except for peat	Distributors and importers.	1990	112 MtCO2e	36%	US$72.8/tCO2e
France	Industry, buildings, and transport (not public) sectors.	Fossil fuels	Distributors and importers.	2014	488 MtCO2e	35%	US$52/tCO2e
Iceland	All sectors but sectors covered by EU ETS are exempt.	Liquid and gaseous fossil fuels	Producers, distributors and importers.	2010	5 MtCO2e	55%	US$35/tCO2e
Ireland	All sectors but sectors covered by EU ETS are exempt.	Fossil fuels	Distributors and importers.	2010	65.6 MtCO2e	49%	US$39/tCO2e
Japan	All sectors with some exemptions.	Fossil fuels	Producers, distributors and importers.	2012	1345 MtCO2e	75%	US$3/tCO2e
Latvia	Industry and power sectors, exempt sectors covered by ETS.	Fossil fuels except for peat	Distributors and importers.	2004	18 MtCO2e	3%	US$14/tCO2e
Liechtenstein	Industry, power, buildings and transport sector	Fossil fuels	Distributors and importers.	2008	0 MtCO2e	26%	US$101/tCO2e
Mexico	Power, industry, transport, buildings, waste, forestry sectors.	All fossil fuels except natural gas.	Producers, distributors and importers.	2014	822 MtCO2e	23%	US$3/tCO2e
Norway	All sectors but EU ETS are exempt.	Liquid and gaseous fossil fuels	Producers, distributors and importers.	1991	75 MtCO2e	66%	US$69/tCO2e
Poland	All sectors but EU ETS are exempt.	Fossil fuels	Users of the fossil fuels.	1990	429 MtCO2e	4%	US$0.08/tCO2e
Portugal	Industry, buildings and transport sectors with some exceptions.	Fossil fuels	Distributors and importers.	2015	81 MtCO2e	29%	US$28/tCO2e
Singapore	Power and industry sectors.	Fossil fuels	Operators at a facility level.	2019	56 MtCO2e	80%	US$4/tCO2e
Slovenia	Buildings and transport sector	Fossil fuels	Distributors and importers.	1996	21 MtCO2e	50%	US$20/tCO2e
South Africa	Industry, power, buildings and transport sector	Not	Users of the fossil fuels.	2019	640 MtCO2e	80%	US$9/tCO2e
Spain	Fluorinated GHG emissions (HFCs, PFCs, and SF6)	Not	The first entry of all F-gases.	2014	367 MtCO2e	3%	US$18/tCO2e
Sweden	Transport and buildings, exempt sectors covered by ETS.	Fossil fuels	Distributors and importers.	1991	111 MtCO2e	40%	US$137/tCO2e
Switzerland	Industry, power, buildings and transport sectors	Fossil fuels	Distributors and importers.	2008	55 MtCO2e	33%	US$101/tCO2e
United Kingdom	Power sector	Fossil fuels	Users of the fossil fuels.	2013	583 MtCO2e	23%	US$25/tCO2e
Ukraine	Industry, power and buildings sectors	Fossil fuels	Users of the fossil fuels.	2011	312 MtCO2e	71%	US$ 0.3/tCO2

Table 3: Descriptive statistics of the samples

Variable	**Mean**	**Median**	**Std. Dev.**	**Mean**	**Median**	**Std. Dev.**
				All countries		
	With carbon tax			without carbon tax		
GDP real (millions 2017US$)	850686.90	393482.88	1082446.42	1121275.39	166135.61	3006622.00
GDP per capita (current US$)	9.89%	10.10%	0.94%	9.11%	9.15%	1.15%
GDP growth (annual %)	2.482	2.683	3.694	3.058	3.254	4.630
Employment rate (% total labor)	92.07%	92.85%	4.75%	92.43%	93.02%	4.45%
Primary energy consumption (TWh)	1094.63	474.96	1379.31	1855.63	254.93	5334.58
clean electricity fraction (% total consumption)	47%	46%	33%	31%	24%	29%
Clean energy fraction (% total consumption)	23%	18%	20%	9%	4%	11%
Countries	23			43		
				Countries with a low carbon intensity energy mix		
	With carbon tax			without carbon tax		
GDP real (millions 2017US$)	609238.88	322000.91	721705.56	654034.94	161623.54	1096710.94
GDP per capita (current US$)	10.02%	10.17%	0.91%	9.26%	9.44%	1.04%
GDP growth (annual %)	2.17	2.57	3.28	2.35	2.67	3.47
Employment rate (% total labor)	92.14%	92.70%	4.51%	90.99%	91.68%	4.23%
Primary energy consumption (TWh)	841.80	351.14	1103.98	748.81	232.82	1166.34
clean electricity fraction (% total consumption)	70%	71%	21%	60%	60%	16%
Clean energy fraction (% total consumption)	36%	32%	17%	23%	23%	8%
Countries	13			12		
				Countries with a high carbon intensity energy mix		
	With carbon tax			without carbon tax		
GDP real (millions 2017US$)	1164569.32	579572.91	1359162.31	1302519.86	168376.80	3459270.47
GDP per capita (current US$)	9.72%	9.86%	0.95%	9.06%	9.07%	1.19%
GDP growth (annual %)	2.89	2.83	4.14	3.33	3.57	4.98
Employment rate (% total labor)	91.97%	93.96%	5.06%	93.06%	93.67%	4.39%
Primary energy consumption (TWh)	1423.29	1010.65	1614.45	2289.49	277.86	6198.64
clean electricity fraction (% total consumption)	16%	12%	15%	19%	10%	24%
Clean energy fraction (% total consumption)	6%	5%	6%	3%	1%	5%
Countries	10			41		

Table 4: Effect of carbon tax on GDP growth rate.

Efecto sobre la tasa de crecimiento del PIB.			
Periodo	TWFE	Sun et. al.	Callaway et. al.
-10	2.0511. (1.0538)	2.072* (0.9154)	-0.066 (0.4674)
-9	2.2377. (1.101)	2.341*** (0.6307)	0.2848 (0.7686)
-8	1.963 (1.0627)	2.098** (0.7346)	-0.2447 (0.7355)
-7	0.3101 (1.2907)	0.4184 (0.9856)	-1.6744* (0.7573)
-6	0.9138 (1.1936)	0.9745 (0.8854)	0.552 (0.9452)
-5	0.9333 (1.1927)	0.9629 (0.65)	-0.0054 (0.7334)
-4	0.548 (1.1334)	0.7931 (0.625)	-0.151 (0.6237)
-3	1.1046 (1.1724)	1.297** (0.4847)	0.5186 (0.6281)
-2	-0.1466 (0.6834)	0.0445 (0.2604)	-1.2647 (0.7162)
-1	-0.0484 (0.7365)	0.6092. (0.2996)	-0.0448 (0.7143)
1	0.9087 (0.6737)	1.543** (0.572)	0.6128 (0.6395)
2	1.0405 (1.047)	1.326*** (0.4413)	1.5846** (0.5919)
3	0.4668 (1.4567)	0.5076 (0.5355)	1.3926* (0.5856)
4	1.7464 (1.2217)	1.707 (1.363)	0.605 (0.6133)
5	3.1444 (1.7416)	3.575 (2.085)	1.7872. (0.9386)
6	0.7838 (1.0323)	1.027 (0.6695)	3.651* (1.6256)
7	0.7748 (1.4977)	1.021 (1.232)	1.1508 (0.6942)
8	2.1321 (1.2189)	2.584. (1.358)	1.1404 (0.9535)
9	1.4368 (1.0582)	2.047 (1.153)	2.676** (0.9565)
10	1.075 (1.6154)	2.086 (1.238)	2.1011* (0.9394)
Fixed-Effects			
Country	Yes	Yes	No
year	Yes	Yes	No
S.E.:Clustered	Country	Country	Country
Observations	2288	2288	2288

Table 5: Effect of carbon tax on GDP growth rate, according to energy matrix

Effect on GDP growth rate				
Periodo	Estimador	Error estándar	Estimador	Error estándar
	Panel A. Países limpios		*Panel B. Países sucios*	
-10	-0.3345	(0.6734)	-0.8265	(0.4406)
-9	-0.2288	(0.5453)	1.2703	(1.2058)
-8	-0.3621	(0.5072)	-0.1283	(1.2226)
-7	-1.499**	(0.5559)	-1.739*	(0.5033)
-6	-0.323	(0.5076)	0.7477	(0.5209)
-5	1.1018*	(0.4524)	-0.831	(0.4793)
-4	-0.4407	(0.4502)	-0.1065	(0.4174)
-3	-0.006	(0.5013)	0.7044	(0.3898)
-2	-1.8644*	(0.5847)	-0.4588	(0.5817)
-1	0.0342	(0.4994)	0.5648	(0.4513)
0	0.5112	(0.5215)	-0.0016	(0.3975)
1	1.8328*	(0.6228)	0.3466	(0.4201)
2	2.024*	(0.6683)	-1.3099*	(0.5608)
3	0.8623	(0.6068)	-2.8622*	(0.764)
4	0.8891	(0.6215)	0.9814	(0.5686)
5	1.3018	(0.733)	4.3461*	(0.9005)
6	0.7619	(0.872)	-0.4006	(0.5029)
7	0.3903	(0.8541)	0.0547	(0.6629)
8	1.661	(0.9432)	1.936*	(0.85)
9	1.0672	(0.7778)	1.5139	(0.8188)
10	0.2729	(0.7947)	2.3459.	(1.1834)

Table 6: Effect of carbon tax on employment rate.

Effect on the employment rate.			
Periodo	TWFE	Sun et. al.	Callaway et. al.
-10	2.6611 (1.5807)	2.447** (0.8509)	0.1847 (1.4704)
-9	2.3939 (1.5619)	2.142* (0.8659)	-0.3068 (1.3768)
-8	2.6395. (1.3626)	2.387** (0.8485)	0.2855 (1.4232)
-7	2.3171 (1.2668)	2.059*** (0.6812)	-0.3256 (1.446)
-6	1.5681 (1.0975)	1.287*** (0.4159)	-0.6085 (1.5235)
-5	1.0559 (1.0219)	0.7722* (0.3419)	-0.5214 (1.4776)
-4	0.9203 (0.9383)	0.6388** (0.24)	-0.1021 (1.6909)
-3	0.8444 (0.8389)	0.5714*** (0.1596)	-0.0635 (1.6412)
-2	0.2272 (0.5176)	0.1457. (0.0749)	-0.3946 (1.6765)
-1	0.0151 (0.3191)	-0.1022 (0.2043)	-0.151 (1.585)
1	-0.0006 (0.3809)	0.0791 (0.4367)	-0.0862 (1.454)
2	-0.5649 (0.7229)	0.0704 (0.6796)	0.1468 (1.6043)
3	-1.1109 (0.8925)	-0.1436 (0.8014)	0.157 (1.4507)
4	-1.7576 (1.2235)	-0.6067 (1.029)	-0.0456 (1.6202)
5	-1.8548 (1.3877)	-0.9074 (1.147)	-0.4825 (2.0502)
6	-1.0674 (1.5969)	-0.4448 (1.358)	-0.7684 (2.0155)
7	-0.9602 (2.1663)	-0.4497 (1.913)	-0.2878 (2.1902)
8	-1.7954 (2.512)	-1.31 (2.309)	-0.2794 (2.4654)
9	-2.809 (2.975)	-1.994 (2.812)	-1.1433 (3.5648)
10	-3.142 (3.1873)	-2.287 (3.054)	-1.8144 (2.3919)
Fixed-Effects			
Country	Yes	Yes	No
year	Yes	Yes	No
S.E.:Clustered	Country	Country	Country
Observations	2288	2288	2288

Table 7: Effect of the carbon tax on the employment rate, according to the energy matrix.

Efecto sobre la tasa de empleo				
Periodo	Estimador	Error estándar	Estimador	Error estándar
	Panel A. Países limpios		*Panel B. Países sucios*	
-10	-0.8827	(2.1563)	0.2963	(0.3754)
-9	1.5237	(1.8727)	0.0085	(0.4002)
-8	-0.3595	(1.6389)	-0.0913	(0.366)
-7	0.1159	(1.4556)	-0.6016	(0.3824)
-6	0.2858	(1.3498)	-0.5876	(0.3664)
-5	0.3304	(0.9291)	0.7763*	(0.3335)
-4	0.8198	(0.7706)	0.353	(0.2958)
-3	0.7605	(0.7469)	0.5847	(0.3161)
-2	-0.5885	(0.7845)	0.2812	(0.3423)
-1	-0.1869	(0.7433)	-0.3589	(0.3377)
0	-0.2718	(0.7126)	-0.161	(0.3283)
1	0.424	(0.6439)	-0.3109	(0.3616)
2	0.9435	(0.6758)	-0.5194	(0.4048)
3	1.3398.	(0.7078)	-0.2784	(0.3922)
4	1.1973	(0.8432)	-0.3419	(0.4487)
5	0.0748	(1.1492)	-0.3159	(0.4802)
6	-0.5212	(1.5708)	-1.3156*	(0.5209)
7	0.3221	(1.0348)	-2.1817*	(0.6321)
8	0.0513	(0.9423)	-1.7983*	(0.7957)
9	-0.3719	(1.0621)	-2.5975**	(0.9207)
10	0.1126	(1.1674)	-5.5129*	(0.9173)

Table 8: Effect of carbon tax on GDP growth rate, according to electricity matrix composition.

Efecto sobre la tasa de crecimiento del PIB				
Periodo	Estimador	Error estándar	Estimador	Error estándar
	Panel A. Países limpios		*Panel B. Países sucios*	
-10	-0.1204	(0.5823)	-0.8602*	(0.4063)
-9	-0.1837	(0.5054)	1.4112	(1.2276)
-8	-0.2729	(0.5652)	-0.0702	(1.2763)
-7	-1.9222*	(0.5846)	-1.6589*	(0.4992)
-6	-0.1248	(0.4972)	0.8153	(0.5344)
-5	1.1171**	(0.4247)	-0.8765	(0.5163)
-4	-0.5326	(0.4392)	-0.1527	(0.4358)
-3	0.1009	(0.4992)	0.7496	(0.4114)
-2	-1.7654*	(0.5608)	-0.4363	(0.5449)
-1	-0.111	(0.5012)	0.4642	(0.4953)
0	0.5908	(0.4877)	-0.0125	(0.4074)
1	1.9277*	(0.599)	0.2502	(0.4246)
2	2.1262*	(0.6625)	-1.4785*	(0.569)
3	1.317*	(0.566)	-2.956*	(0.8038)
4	1.4174*	(0.6158)	0.8687	(0.6318)
5	1.9908**	(0.7196)	4.2354*	(0.9454)
6	1.3091	(0.8273)	-0.5926	(0.5206)
7	0.4475	(0.8145)	-0.1533	(0.7561)
8	2.1054*	(0.8762)	1.6759.	(0.8269)
9	1.6742*	(0.7858)	1.4351	(0.7959)
10	1.081	(0.7777)	2.1487	(1.2084)

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