Can growth take place while reducing emissions?

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Abstract. This study aims to determine whether the economic effect of introducing a carbon tax differs between countries, according to the energy mix of clean and polluting inputs. Following a model of directed technical change and environmental, I empirically analyze the implementation of a carbon tax in countries with different carbon-intensity energy sources and the allocation of revenues. 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 in the energy mix increases. (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. These results are consistent with the predictions of the theoretical model and suggest that policymakers could consider this relationship between the energy mix and the economic effect of a carbon tax when creating environmental regulations.

Keywords: Carbon tax, Directed Technical Change, Climate change and Environment.
JEL Codes: O1, O4, Q4, Q5, O57.

1 Introduction

Since 2012 with the DOHA Amendment and later in 2015 with the Paris Agreement, there has been a growing effort to implement policies for mitigating and adapting to climate change (Delmotte, 2021, Rodríguez, 2015). One of the greatest challenges that countries face is acting against climate change while minimizing the negative effects on economic growth. Historically, CO2 emissions have been strongly correlated with economic growth. The richer we are, the more CO2 we emit. This is because we use more energy, which often comes from burning fossil fuels. However many countries have decoupled economic growth from CO2 emissions. This implies that other factors, such as the energy intensity (energy consumed per unit of GDP) and the intensity of carbon emissions (CO2 emitted per unit of GDP), also play an important role in decarbonization.

According to the Kaya identity (Kaya, Yokobori, et al., 1997), there are two strategies to reduce CO2 emissions without affecting GDP per capita. The first method involves reducing energy intensity by improving energy efficiency, shifting to industries that consume less energy, or both. The second method entails reducing carbon intensity by replacing fossil fuels with renewable energy sources. By implementing these

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measures, it would be possible to decrease CO2 emissions while maintaining economic growth. Therefore, this study aims to determine whether the effect of introducing a carbon tax on GDP growth and employment rate differs between countries depending on the combination of energy sources.

Until 2021, there are 68 direct carbon pricing instruments operating today: 36 carbon taxes and 32 Emissions Trading Systems (ETSs). One of the most widely used climate policy tools is the carbon tax. This tax creates incentives for countries to switch to less carbon- and energy-intensive forms of production. This process generates an adaptation cost for both workers and producers of goods and services (Nordhaus, 1991; Pearce, 1991). However, these adaptation costs may depend on the characteristics of each country, such as the primary energy sources required in the final production, that is, the energy matrix.

The carbon tax assigns a cost to the tons of carbon dioxide (CO2) emissions, in this way the emitters internalize the social effect generated by pollution, therefore, firms and consumers have incentives to use non-exhaustible sources of energy and /or adopt new technologies that reduce their emissions. From the point of view of economic theory, the energy transition can be considered as a process of creative destruction, where the consolidation of the “clean” sector, whose energy comes from renewable sources, displaces the “dirty” sector, which consumes energy from fossil fuels (Torres, 2021). On the one hand, the carbon tax increases the cost of each unit produced with polluting energy sources, thereby reducing the relative demand for “dirty” inputs and reducing the benefits of innovating in this sector. On the other hand, investment in research and development in the “clean” sector stimulates innovation, therefore, the growth of the clean sector is accelerated.

The energy mix is the combination of primary energy sources required to guarantee the energy consumption of a country. Several academics [1] have shown that energy consumption is strongly related to Gross Domestic Product (GDP), therefore, the share of primary energy sources is expected to influence the effect of the carbon tax on economic growth and employment.

This article contributes to the literature in three ways. First, I present an extension to Acemoglu et al. (2012a) in order to incorporate the effect of carbon taxes and clean production subsidies, and derive conditions under which the effect on the growth rate is positive. Second, I test the main results derived from the theoretical model. For this purpose, I consider the initial ratio of clean and dirty energy sources into the growth rate equation. Third, with this procedure, I identify heterogeneous effects of the introduction of the carbon tax depending on the composition of the energy matrix. The literature has analyzed the macroeconomic effect of the carbon tax. However, to the best of my knowledge, this source of heterogeneity has not been studied empirically.

I show that a greater share of primary renewable energy sources reduces the negative effect of the carbon tax on the rate of economic growth. Furthermore, if the tax proceeds are used to subsidize clean technology research, the net effect of the tax on growth may

[1] Kraft and Kraft (1978), Ozturk (2010), Narayan and Smyth (2008), among others.

be positive. Beyond these analysis and results, the paper contributes more generally to the issue of how to achieve economic growth while reducing CO emissions, emphasizing the role of energy sources.

There exists a rich literature on the effects of a carbon tax on macroeconomic outcomes. Bernard et al. (2018) and Metcalf and Stock (2020) do not find adverse impacts of the carbon tax on 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 and Steiner (n.d.)). A study by Andersson J (2017) found that for necessary goods (goods with income elasticity less than one), the greater the income inequality, the greater the regressiveness of a tax on fuel consumption, transportation, heating, power generation, and electricity.

In the context of energy sources and the carbon tax, the literature is limited. On the one hand, Papageorgiou et al. (2017) estimated the elasticity of substitution between energy inputs from clean and dirty sources. 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 explores how the different combinations of energy sources can influence the effect of implementing climate policies, such as the carbon tax.

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., 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 and Romer, 2010 and Laffont and Martimort, 2009). In particular, some authors have analyzed theoretically and empirically how innovations and directed technological 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.

The remainder of the paper is organized as follows. Section II presents the theoretical model(Acemoglu et al. (2012a)), the autarky equilibrium, and the framework when a dirty production tax is implemented. Also, this section presents the growth rate equation considering the initial share of primary energy sources, and describes the three corollaries that follow from the growth equation. Section III presents the data and methods used for the estimation of the impact of the carbon tax on the GDP growth rate and the employment rate, and the heterogeneities according to the share of the energy matrix. Section IV presents and discusses the results of the empirical analysis as well as the relationship with the corollaries. Finally, Section VI concludes.

2 Solving the model with an optimal environmental policy.

In this model, a final good is created by combining inputs from two sectors: one that uses "clean" energy sources and another that uses "dirty" sources. These sectors' inputs are substitute goods, which means they can be used interchangeably to produce the final good. Innovation can occur in both the clean and dirty sectors, with intermediate goods purchasing patents. Labor is assumed to be mobile, so there are no differentiated wages. However, if production is done with dirty sources, the environmental quality degrades, which can lead to an environmental disaster and make production impossible. Taxes can be used to incentivize innovation to the clean sector, thereby preventing environmental degradation and ensuring long-term production.

Following the model of directed technological change with environmental constraints developed by Acemoglu et al. (2012a), I explore how a carbon tax affects GDP growth, focusing on how this impact varies depending on the share of primary energy sources. Based on the model's specifications, I propose a hypothesis and three corollaries that can be empirically tested to determine the impact of a carbon tax on economic growth.

2.1 Conceptual framework

Environmental policy must ensure that the demand for dirty inputs takes into account the environmental cost of an additional unit of the dirty input. The letter θ is used to represent this cost, which is measured in terms of units of the dirty input $f(\xi)$. I assume a balanced budget with an environmental policy, which means that tax revenue equals subsidy spending. As a result, I determine the clean technology subsidy as a function of the carbon tax rate multiplied by the ratio of dirty to clean input production.

$$q_t = \tau_t \cdot \frac{Y_{dt}}{Y_{ct}} = \tau_t \cdot \Phi_t \tag{1}$$

Final good production As mentioned above, the final good is produced from "clean" and "dirty" inputs. Each country is inhabited by a continuum of households comprising workers, entrepreneurs and scientists. Households have the following preferences:

$$\sum_{t=0}^{\infty} \frac{1}{(1+\rho)^t} u(C_t, S_t) \tag{2}$$

Where C_t is consumption of the unique final good at time t, S_t denotes the quality of the environment at time t and $\rho > 0$ is the discount rate. I assume that $S_t \in [0, \bar{S}]$, where $\bar{S}$ is the quality of the environment absent any human pollution, that is $S_0 = \bar{S}$. In particular, an environmental catastrophe occurs if $S_t = 0$.

There is a unique final good, Y_t, produced competitively using "clean" and "dirty" inputs (depending on primary energy source required), Y_c y Y_d, according to the aggregate production function:

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

where $\epsilon \in (0, +\infty)$ is the elasticity of substitution between the two sectors. If the inputs are (gross) substitutes, $\epsilon > 1$, then any production of the final good can be obtained from alternative clean energies. For example, renewable energy, provided it can be stored and transported efficiently, may replace energy derived from fossil fuels. On the contrary, if the two inputs are (gross) complements, $\epsilon < 1$, then it is impossible to produce without fossil fuels and the environmental catastrophe is unavoidable.

Each of the inputs is produced symmetrically, in perfect competition at a price P_{it}. Using the final good as the numeraire, the price of the inputs that the producer of the final good must pay is:

$$\left((1-\tau_t\Phi)P_{ct}^{1-\epsilon} + (1+\tau_t)P_{dt}^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}} = 1 \tag{4}$$

The tax is charged on the price paid by the producer of the final good for each unit of the dirty inputs demanded, which means that the relative demand for dirty and clean inputs are:

$$\begin{aligned} \left(Y_{dt}^{\frac{\epsilon-1}{\epsilon}} + Y_{ct}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{1}{\epsilon-1}} \times Y_{dt}^{-\frac{1}{\epsilon}} &= P_{dt}(1+\tau_t) \\ \left(Y_{dt}^{\frac{\epsilon-1}{\epsilon}} + Y_{ct}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{1}{\epsilon-1}} \times Y_{ct}^{-\frac{1}{\epsilon}} &= P_{ct}(1-\tau_t\Phi) \end{aligned} \tag{5}$$

On the demand side, the prices of dirty goods exhibit a negative correlation with the carbon tax, while the prices of clean goods have a positive correlation with the subsidy ($\tau\Phi$). In other words, the carbon tax raises the prices of final dirty goods, reducing their demand. In contrast, the subsidy lowers the prices of clean goods, increasing their demand.

$$\begin{aligned} P_{dt} &= \frac{Y_{dt}}{Y}^{-\frac{1}{\epsilon}} \frac{1}{1+\tau} \\ P_{ct} &= \frac{Y_{ct}}{Y}^{-\frac{1}{\epsilon}} \frac{1}{1-\tau\Phi} \end{aligned} \tag{6}$$

so, relative input demand is:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{dt} \cdot 1 + \tau_t}{P_{ct} \cdot 1 - \tau_t\Phi}\right)^{\epsilon} \tag{7}$$

The two inputs, Y_c and Y_d, are produced using labor L_{jt} and a continuum of sector-specific machines (intermediates) x_{jit}. The production of inputs is given by:

$$Y_{jt} = L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} \cdot di \tag{8}$$

where $j \in (c, d)$ denotes the sector, A_{jit} is the quality of machine i, and x_{jit} is the quantity of this machine i used in sector j at time t.

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.

$$\max_{x_{jit}, L_{jt}} \left\{ P_{jt} L_{jt}^{1-\alpha} \int_0^1 A_{jit}^{1-\alpha} x_{jit}^{\alpha} \cdot di - w_{jt} L_{jt} - \int_0^1 p_{jit} x_{jit} \cdot di \right\} \tag{9}$$

where w_{jt} denotes the wage paid for each unit of labor hired in each sector j and p_{jit} is the price that the producer of inputs must pay for each machine i used. Machines are of different quality and technological progress occurs as the quality of machines increases, so the productivity of a sector is the average productivity of machines in that sector.

From the first-order conditions is obtained the demand for machines in the two sectors:

$$x_{jit} = \left(\frac{\alpha P_{jt}}{p_{jit}} \right)^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \tag{10}$$

and, the demand for labor:

$$L_{jt} = \left(\frac{(1-\alpha) P_{jt}}{w_{jt}} \right)^{\frac{1}{\alpha}} A_{jit}^{\frac{1-\alpha}{\alpha}} x_{jit} \tag{11}$$

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

$$\pi_{jt} = (p_{jit} - \varphi) \left(\frac{\alpha P_{jt}}{p_{jit}} \right)^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \tag{12}$$

Because machines depreciate as they are used, Acemoglu et al., 2012a normalize $\varphi = \alpha^2$, so, each monopolist sets a price that supplies the demand of the market $p_{jt} = \alpha$. Thus, replacing price of machine p_{jit} in equation 10, the optimal demand for machines in each sector is obtained:

$$x_{jit} = (P_{jt})^{\frac{1}{1-\alpha}} A_{jit} L_{jt} \tag{13}$$

and the quantities of inputs produced in sector j is:

$$y_{jt} = A_{jit} L_{jt} (P_{jt})^{\frac{\alpha}{1-\alpha}} \tag{14}$$

Combining this equation 12 and replacing φ, the equilibrium profits of machine producers can be written as:

$$\pi_{jt} = (1-\alpha) \alpha P_{jt}^{\frac{1}{1-\alpha}} A_{jit-1} L_{jt} \tag{15}$$

Technological change Successful innovation for a given machine increases the quality of a machine by a factor $1+\gamma$ and happens with probability $\mu_j \in (0,1)$ in sector $j \in (c,d)$. I normalize the measure of scientists s to 1 and denote the mass of scientists who direct their effort to sector j, s_{jt}, therefore, the specification for the innovation possibilities frontier implies that A_{jt} is defined as:

$$A_{jt} = (1+\gamma\mu_j s_{jt})A_{jt-1} \tag{16}$$

In order to innovate the entrepreneur must conduct research, a costly activity that uses the final good as input. The probability μ_{jt} that an innovation occurs in sector j any period t depends positively on the amount of research expenditure R_t, and depends inversely on productivity in the initial period A_{jit-1}. The reason is that as technology advances it becomes more complex and thus harder to improve upon. The probability function of success is:

$$\mu_{jt} = \lambda\left(\frac{R_{jt}}{A_{jit-1}}\right)^{\sigma} \tag{17}$$

The parameter λ reflects the productivity of research expenditure, and the elasticity parameter σ lies between zero and one. In this context, I adopt the assumptions of Aghion and Howitt (1992) regarding the innovator's problem, and I fix the values of λ and σ at 2 and $\frac{1}{2}$, respectively.

The problem for entrepreneurs is to maximize the probability of innovating μ_{jt} in each sector j, which depends on the price of the patent P_{Ajit}, and R&D investment R_{jt}, that is,

$$\max_{\mu_{jt}} \{\mu_{jt}P_{Ajit} - R_{jt}\ \} \tag{18}$$

Maximizing with respect to R_{jt}, I get:

$$\frac{R_{jt}}{A_{jit-1}} = \left(\frac{P_{Ajt}\lambda\sigma}{A_{jit-1}}\right)^{\frac{1}{1-\sigma}} \tag{19}$$

Replacing equation 19 in equation 17, and as I know, the price of the patent is equal to the net profits of machine producer $P_{Ajit} = \pi_{jit}$, (equation 15), then the probability of innovating in each sector is:

$$\mu_{jt} = \alpha(1-\alpha)\gamma^{-1}P_{jt}^{\frac{1}{1-\alpha}}L_{jt} \tag{20}$$

2.2 Optimal policy

To determine the relative price of inputs between sectors, I substitute the demand for machines equation 10 into the demand for labor equation 11:

$$P_{jt} = \left(\frac{w_{jt}}{(1-\alpha)A_{jit}}\right)^{1-\alpha} \tag{21}$$

Since equilibrium wages are equal, $w_{ct} = w_{dt}$, the relative price of inputs is:

$$\frac{P_{ct}}{P_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{-(1-\alpha)} \tag{22}$$

Taking the input quantities equation 14 and the relative input demand equation 7, I get:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{ct}}{P_{dt}}\right)^{\frac{\alpha}{1-\alpha}} \frac{A_{ct}}{A_{dt}} \frac{L_{ct}}{L_{dt}} = \left(\frac{P_{dt} \cdot 1 + \tau_t}{P_{ct} \cdot 1 - \tau_t \Phi}\right)^{\epsilon} \tag{23}$$

Equation 23 shows that the tax has no impact on production costs, but it does affect the demand for final goods in each sectors. Tax, in particular, increases demand for clean goods while decreasing demand for dirty ones. As a result, producers of intermediate goods have an incentive to offer more clean goods, resulting in an increase in labor and productivity associated with clean intermediate goods (L_{ct} and A_{cit}). By replacing the relative prices with equation 21, I can derive the relative demand for labor.

$$\frac{L_{ct}}{L_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{(1-\alpha)(\epsilon-1)} \cdot \left(\frac{1 - \tau_t}{1 + \tau_t \Phi}\right)^{\epsilon} \tag{24}$$

Since the relative probability of obtaining an innovation in the clean sector is:

$$\frac{\mu_{ct}}{\mu_{dt}} = \left(\frac{P_{ct}}{P_{dt}}\right)^{\frac{1}{1-\alpha}} \times \left(\frac{L_{ct}}{L_{dt}}\right) \tag{25}$$

and, it can be written as follows:

$$\frac{\mu_{ct}}{\mu_{dt}} = \left(\frac{A_{ct-1}}{A_{dt-1}}\right)^{(1-\alpha)(\epsilon-1)-1} \times \left(\frac{1 - \tau_t}{1 + \tau_t \Phi}\right)^{\epsilon} \tag{26}$$

In the absence of any environmental policy, the relative benefits of innovating are always greater in the sector with the highest technological level. So the tax by changing the demand for final goods may increase the production of clean inputs, making the labor force in this sector more productive. As a result, the tax can increase the probability of innovating in the clean sector rather than the dirty.

$$\tau > \frac{1}{1 - \Phi} \left(1 - \frac{A_{dt}}{A_{ct}}\right)^{\frac{(1-\alpha)(\epsilon-1)-1}{\epsilon}} \tag{27}$$

Equation 27 shows that the technological gap between the dirty sector and the clean sector is a direct function of the ratio of dirty to clean production, Φ_t. Also shows that the more technologically the clean sector lags behind the dirty, the larger the subsidy must be to direct R&D resources to the clean sector. Since the subsidy is composed of the ratio in clean and dirty production and the tax, the tax should be greater. This tax rate makes the technological level of the clean sector grow faster than in the dirty sector.

2.3 The aggregate productivity growth rate.

In order to measure the total change in output growth, I start from the aggregate production function equation 3:

$$Y_t^{\frac{\epsilon}{\epsilon-1}} = Y_{ct}^{\frac{\epsilon-1}{\epsilon}} + Y_{dt}^{\frac{\epsilon-1}{\epsilon}} \tag{28}$$

So, the derivative of dirty and clean production are:

$$\begin{aligned} \frac{\partial Y_t}{\partial Y_{dt}} &= \left(\frac{Y_t}{Y_{dt}}\right)^{\frac{\epsilon-1}{\epsilon}} \\ \frac{\partial Y_t}{\partial Y_{ct}} &= \left(\frac{Y_t}{Y_{ct}}\right)^{\frac{\epsilon-1}{\epsilon}} \end{aligned} \tag{29}$$

Combining the equations 28 and 29 and dividing by Y, I get:

$$\frac{\Delta Y_t}{Y} = \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\Delta Y_{dt}}{Y_{dt}} + \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\Delta Y_{ct}}{Y_{ct}} \tag{30}$$

Where $\frac{Y_{jt}}{Y}$ is the initial production of each sector. Since the growth of the economy is given by the equilibrium between firms, combining the production function of final goods equation 8 with the supply of intermediate goods equation 14 I find the growth of production in each sector is given by:

$$\frac{\Delta Y_j}{Y_{jt}} = \frac{\Delta A_j}{A_{jt}} + \frac{\Delta L_j}{L_{jt}} \tag{31}$$

From the Schumpeterian model, in equation 37 I know that the economic growth rate is proportional to the frequency of innovating and the size of the innovations.

$$\frac{\Delta A_j}{A_j} = \mu_j(\gamma - 1) \tag{32}$$

So the GDP growth can be expressed as:

$$\frac{\Delta Y_t}{Y} = \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \left[\mu_d(\gamma - 1) + \frac{\Delta L_d}{L_d}\right] + \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \left[\mu_c(\gamma - 1) + \frac{\Delta L_c}{L_c}\right] \tag{33}$$

Using equation 15 to replace μ_j in the sector j, I obtain the following expression:

$$\begin{aligned} \frac{\Delta Y_t}{Y} = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} &\cdot \left[\alpha(1-\alpha)P_{ct}^{\frac{1}{1-\alpha}} L_{ct}\gamma^{-1} \cdot (\gamma - 1) + \frac{\Delta L_c}{L_{ct}}\right] + \\ \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} &\cdot \left[\alpha(1-\alpha)P_{dt}^{\frac{1}{1-\alpha}} L_{dt}\gamma^{-1} \cdot (\gamma - 1) + \frac{\Delta L_d}{L_{dt}}\right] \end{aligned} \tag{34}$$

Substituting the demand prices of the inputs, equation 6:

$$\begin{aligned}\frac{\Delta Y_t}{Y} = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \left[\alpha(1-\alpha)\left(\frac{Y_{ct}}{Y}^{-\frac{1}{\epsilon}}\frac{1}{1-\tau\Phi}\right)^{\frac{1}{1-\alpha}} L_{ct}\gamma^{-1}\cdot(\gamma-1)+\frac{\Delta L_c}{L_{ct}}\right]+ \\ \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \left[\alpha(1-\alpha)\left(\frac{Y_{dt}}{Y}^{-\frac{1}{\epsilon}}\frac{1}{1+\tau}\right)^{\frac{1}{1-\alpha}} L_{dt}\gamma^{-1}\cdot(\gamma-1)+\frac{\Delta L_d}{L_{dt}}\right]\end{aligned} \tag{35}$$

The aggregate productivity growth is given by[2]:

$$\begin{aligned}\frac{\Delta Y_t}{Y} = \left(\frac{Y_{ct}}{Y}^{\frac{\varphi-1}{\epsilon(1-\alpha)}}(1-\tau\Phi)^{-\frac{1}{1-\alpha}}L_{ct}+\frac{Y_{dt}}{Y}^{\frac{\varphi}{\epsilon(1-\alpha)}}(1+\tau)^{-\frac{1}{1-\alpha}}L_{dt}\right)\cdot\alpha(1-\alpha)\frac{\gamma-1}{\gamma}+ \\ \left(\frac{Y_{ct}-Y_{dt}}{Y}\right)^{\frac{\epsilon-1}{\epsilon}}\cdot\frac{\Delta L_c}{L_c}\end{aligned} \tag{36}$$

Equation 36 shows that the carbon tax negatively affects the growth rate of the polluting sector, and increases the growth rate of the clean sector, when the tax revenue is invested in R&D in the clean sector. The initial *share of production* of clean inputs $\frac{Y_{ct}}{Y}$, and of dirty inputs $\frac{Y_{dt}}{Y}$ alters the total effect of the tax on the growth rate of the economy.

Proposition 1: *If clean and dirty inputs are strong substitutes ($\epsilon > 1$) a carbon tax τ is implemented while tax revenues are invested in the clean sector. Then the effect of introducing a carbon tax on the GDP growth rate g_t, is an increasing function of the initial share of clean sector in the production. The greater the initial participation of the clean sector in the final product, the greater the positive effect of carbon tax on growth rate. See figure 1.*

Proof The change in the growth rate given the existence of a carbon tax is expressed by:

$$\begin{aligned}\frac{\partial\frac{\Delta Y_t}{Y}}{\partial\tau_t} = \left(\Phi\frac{Y_{ct}}{Y}^{\frac{\varphi-1}{\epsilon(1-\alpha)}}(1-\tau\Phi)^{\frac{\alpha-2}{1-\alpha}}L_{ct}-\frac{Y_{dt}}{Y}^{\frac{\varphi-1}{\epsilon(1-\alpha)}}(1+\tau)^{\frac{\alpha-2}{1-\alpha}}L_{dt}\right)\cdot\frac{\alpha(\gamma-1)}{\gamma}+ \\ \frac{\partial\frac{\Delta L_c}{L_c}}{\partial\tau_t}\cdot\left(\frac{Y_{ct}-Y_{dt}}{Y}\right)^{\frac{\epsilon-1}{\epsilon}}\end{aligned} \tag{37}$$

This proposition yields an important insight: a carbon tax combined with a clean input subsidy accelerates clean sector productivity while decelerating dirty sector productivity. As a result, the net effect of the carbon tax on economic growth varies depending on the relative share of production sectors. If the share of clean inputs in

[2] For simplicity $\varphi = (\epsilon-1)(1-\alpha)$ and $\psi = \alpha(1-\alpha)\frac{\gamma-1}{\gamma}$

production exceeds a critical level relative to dirty production, imposing a carbon tax may have a positive impact on the economy's growth rate.

The tax has the effect of reducing the demand for dirty final goods. However, it may not necessarily increase productivity in the production of clean final goods. Therefore, the net effect on the GDP growth rate may be negative.

The second part of the equation refers to the effect of the carbon tax on the change in employment in the clean sector. From this, it can be concluded that in the long term, once the production of clean inputs exceeds the production of dirty inputs, the effect on the growth rate will be positive. In addition, equation 23 shows that the carbon tax increases employment in the clean sector and discourages employment in the dirty sector, through a change in demand.

To provide a quantitative understanding of the implications of the energy mix, I 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 at different rates of production of clean and dirty inputs in their initial state. I chose the parameters using Acemoglu et al. (2012a) parameters, where $\gamma = 2$, $\alpha = 0.3$, and $\epsilon = 3$. I only considered one period, namely period $t+1$, after one year of implemented a carbon tax.

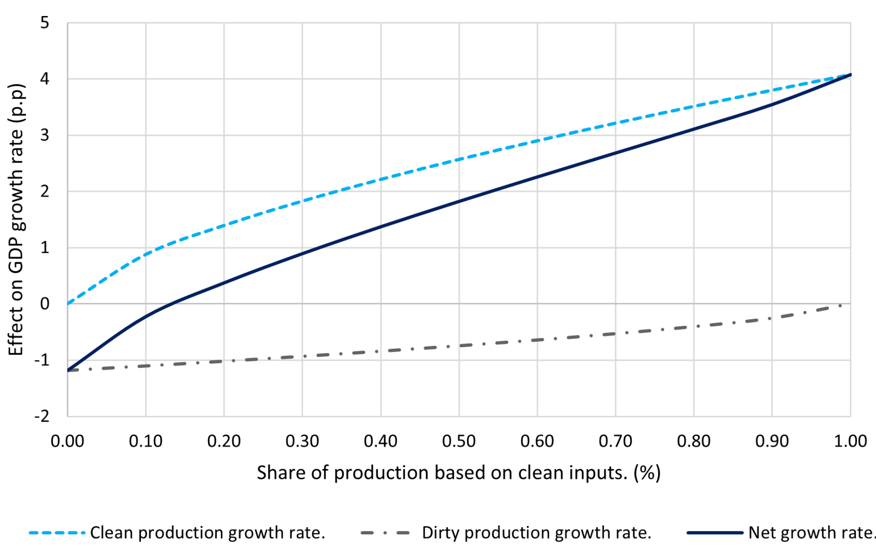


Fig. 1: Graphic representation of the effect of the carbon tax on the growth rate (g_t/τ), according to the initial share of clean inputs in total production.

Corollary 1: *When the share of the clean sector on the final production is lower than a certain critical level, relative to the dirty sector,* $\frac{Y_{ct}}{Y_{dt}} < \theta$*, the effect of the carbon tax on the growth rate of the economy is negative.*

Corollary 2: *When the share of the clean sector on the final production is greater than a certain critical level, relative to the dirty sector,* $\frac{Y_{ct}}{Y_{dt}} > \theta$*, the effect of the carbon tax on the growth rate of the economy is likely to be positive.*

Corollary 3: *In countries where the share of the "dirty" sector is initially large relative to the "clean" sector, the introduction of a carbon tax will initially have a negative effect on the growth rate. This effect will dissipate over time as the productivity of technologies in the "clean" sector outperforms the "dirty" sector, so in the long run the effect is likely to be positive.*

3 Empirical methodology

3.1 Data

To empirically analyze the effect of a carbon tax on GDP growth and employment rates, I use 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 number of employees over economically active population (%).

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.*

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.

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. The figure 2 shows the share of energy from low-carbon intensity sources by countries.

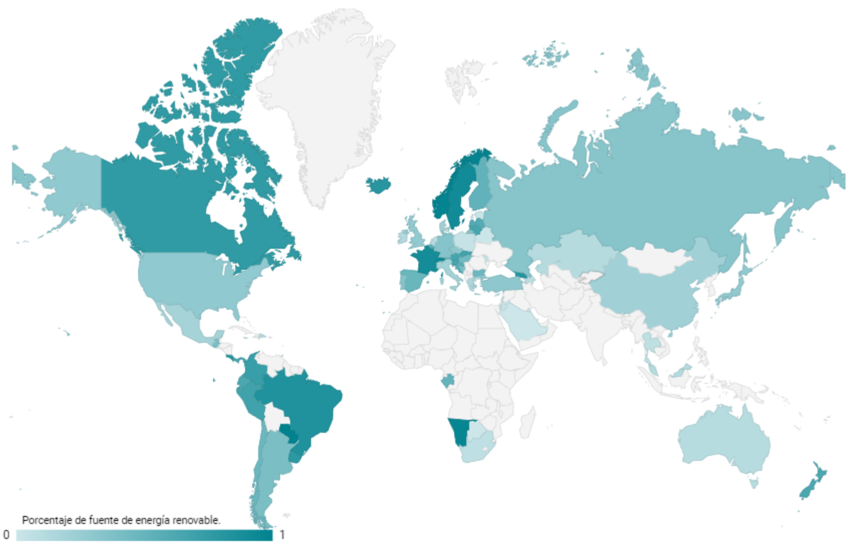


Fig. 2: Map of countries according to the share of clean energy sources

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. The 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.

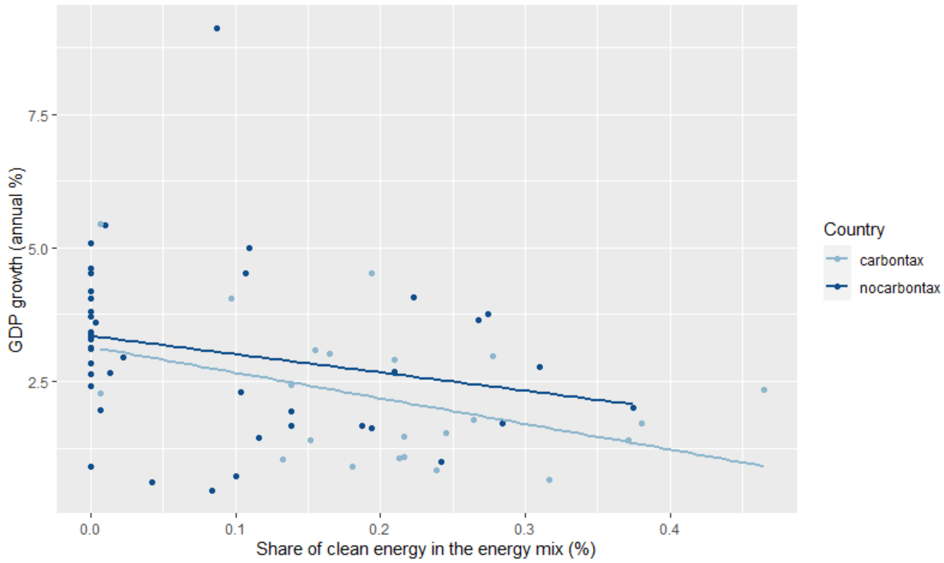


Fig. 3: The relationship between GDP growth and the proportion of clean energy sources in the energy mix

3.2 Empirical strategy

In this paper, I estimate the effect of introducing a carbon tax on macroeconomic variables, according to the primary energy sources of consumption, in order to validate the corollaries defined in the theoretical model. For this, I use the event study method with the estimators proposed by Callaway and Sant'Anna, 2021, Sun and Abraham, 2021 and TWFE (Two Way Fixed Effects).

Event Study is used to estimate the effect of introducing a carbon tax on macroeconomic variables: GDP growth rate and employment rate. In this approach, I aim to estimate the effect on GDP which is not associated with its historical economic growth. I assume that changes in GDP not predicted by historical GDP growth in the country itself, nor by current and past international economic shocks, are exogenous. Several studies have used the event study strategy to analyze the effects of regulatory changes on carbon prices, energy and stock prices (Mansanet-Bataller and Pardo, 2009; Fan et al., 2017; Bushnell et al., 2013, among others).

We introduce the following assumptions, which captures the effect of carbon tax on GDP and employment rate: *Treatment timing*. The treatment time assumption refers to a scenario in which there are several time periods and countries implement a carbon tax at any time within those periods. Once a country implements the tax, it remains in treatment for the remainder of the time period. This assumption implies that the timing of the implementation of the tax is unrelated to other factors such as GDP that may influence the outcome, meaning that it is considered exogenous. In other words, the timing of tax implementation is independent of other factors and is not influenced by them.

No-anticipation assumption. The implementation of the carbon tax does not affect the path of GDP or labor force outcomes prior to the treatment period. In other words, the counterfactual outcome paths for GDP and employment rate in periods prior to the treatment period would have been the same whether or not the carbon tax had been implemented at some point in the future. Similarly, the treatment assignment does not depend on the potential outcomes of GDP or employment rate in any period.

Parallel trends. The parallel trends assumption in the context of a staggered events study with a carbon tax as the treatment and GDP and employment rate as the outcome variables would imply that in the absence of the carbon tax, the trends in GDP and employment rate would be parallel across the treated and control groups. In this study, any differences in the post-treatment outcomes between the two groups can be attributed to the treatment (i.e., the carbon tax) and not to pre-existing differences in the trends of GDP and employment rate.

Effect of a carbon tax in countries with high-carbon energy sources.

Corollary 1 states that the effect of the carbon tax on the growth rate of the economy is negative if the share of the polluting sector in final output is greater than a critical level relative to the share of the clean sector, $\frac{Y_{ct}}{Y_{dt}} < \theta$. To test this empirically I use the empirical event study strategy and the subsample of "polluting countries", consisting of those countries whose share of clean sources is below the average.

In this model, I consider the year in which the carbon tax was introduced as year 0. I then define the periods before ($t < 0$) and after ($t > 0$) the introduction of the carbon tax, and I align time t=0 for all countries in the treatment group. I assume that the evolution of the potential outcome in the absence of the treatment can be decomposed into a time fixed effect. Based on this assumption, I estimate the average dynamic effect of introducing a carbon tax on the GDP and employment growth ($Y_{c,t}$) in country c and year t. To conduct our analysis, I employ equation 38.

$$Y_{c,t} = \beta_1 \sum_{-T \leq r \leq T}^{r \neq 0} 1\left[CarbonTax_{c,t} = r\right] + \Phi_c + \Phi_t + \epsilon_{c,t} \tag{38}$$

where $Y_{c,t}$ is the GDP growth rate and employment rate. β_1 measures the average dynamic effect of carbon tax in the sample of "polluting countries". When the outcome variable is the GDP growth rate this estimator tests the *corollary 1.* 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. With the Callaway et al. estimator I exclude these fixed effects such that the resulting estimator will be the canonical average treaty treatment estimator. All econometric exercises include country-level clustering in order to control for the variance of the within-country errors.

Effect of a carbon tax in countries with low-carbon energy sources.

Corollary 2 establishes that the carbon tax favors economic growth if the share of the clean sector in final production is greater than a critical level relative to the share of the polluting sector, $\frac{Y_{ct}}{Y_{dt}} > \theta$. To empirically test corollary 2 I use the event study strategy and the subsample of "clean countries", consisting of those countries whose share of clean sources is above the country average (above 14%).

Using equation 39 I estimate the average dynamic effect of introducing a carbon tax on GDP growth rate and employment rate $Y_{c,t}$ in countries that have a clean energy matrix.

$$Y_{c,t} = \beta_1 \sum_{-T \leq r \leq T}^{r \neq 0} 1\left[CarbonTax_{c,t} = r\right] + \Phi_c + \Phi_t + \epsilon_{c,t} \tag{39}$$

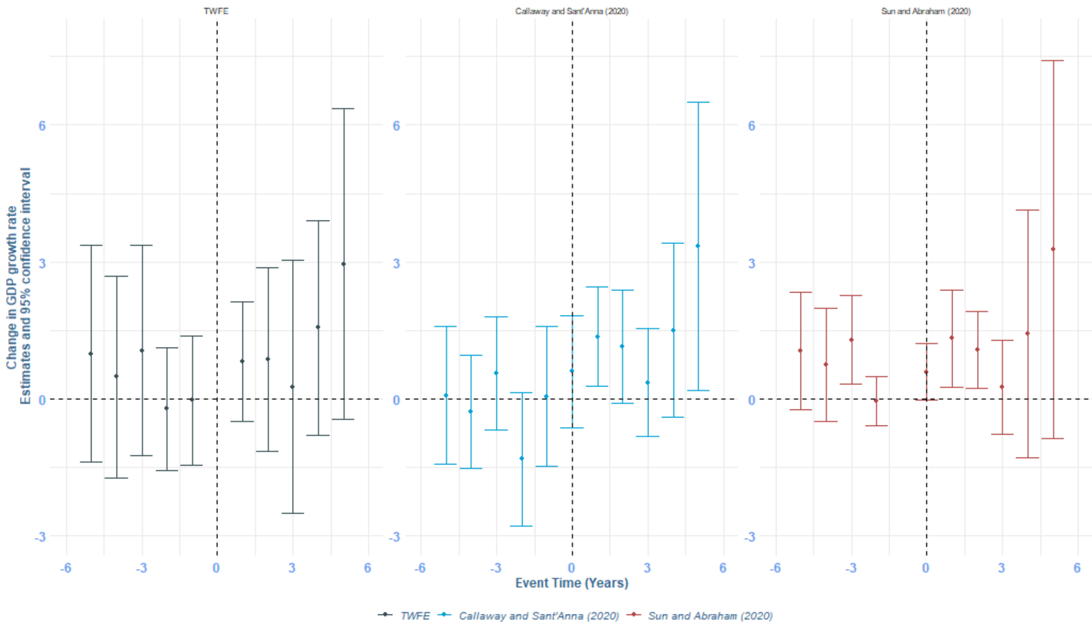
$Y_{c,t}$ is the GDP growth rate and employment rate. β_1 measures the average dynamic effect of climate policy, in the sample of "clean countries". When the outcome variable is the economic growth rate this estimator tests the *corollary 2*. I include α_c country fixed effects c for unobserved country-specific characteristics and Φ_t time fixed effects t.

4 Results

4.1 Effect 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.

Fig. 4: Effect 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.

Fig. 5: Effect of the carbon tax on employment rate.

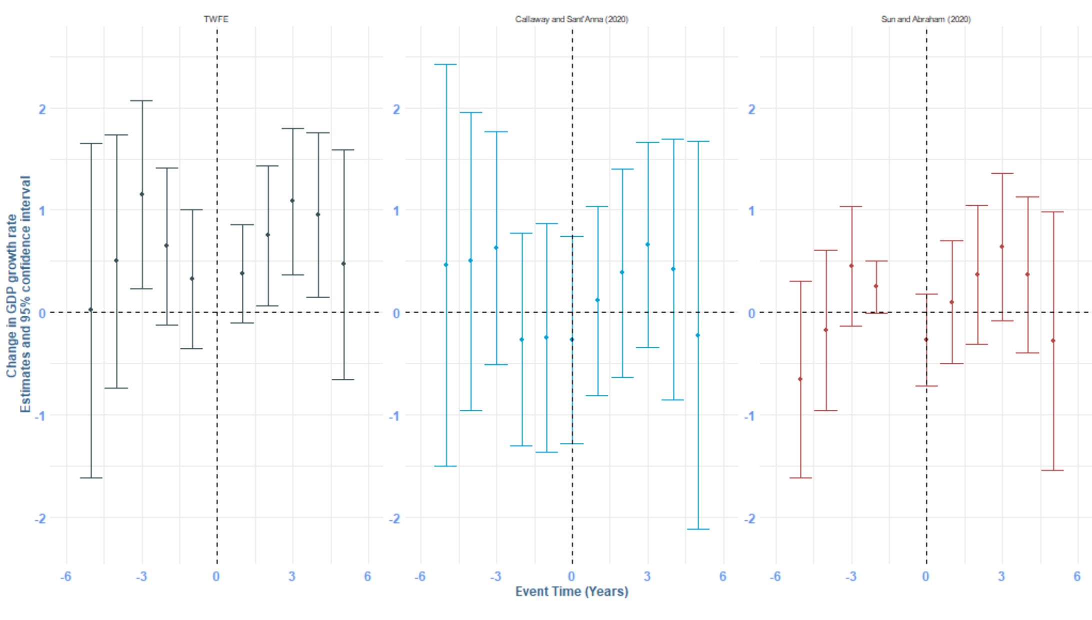


Figure 5 presents the results of the effect of the carbon tax on the employment rate using the whole sample. There is evidence of a decrease in the employment rate after the third and fourth year, but there is no statistical significance in any of the estimators 6. It could be argued that the carbon tax is not associated with changes in the employment rate in the first three years after 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. In order 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.

Effect of the carbon tax in polluting countries. In order 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.

Fig. 6: Annual GDP growth (%) in countries with a polluting energy matrix.

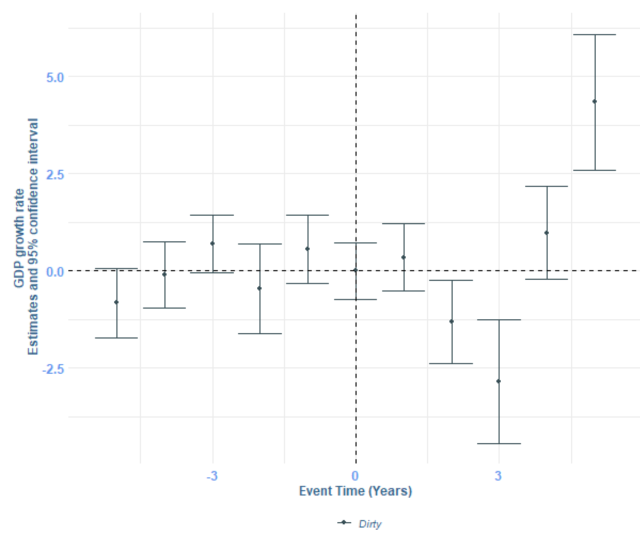
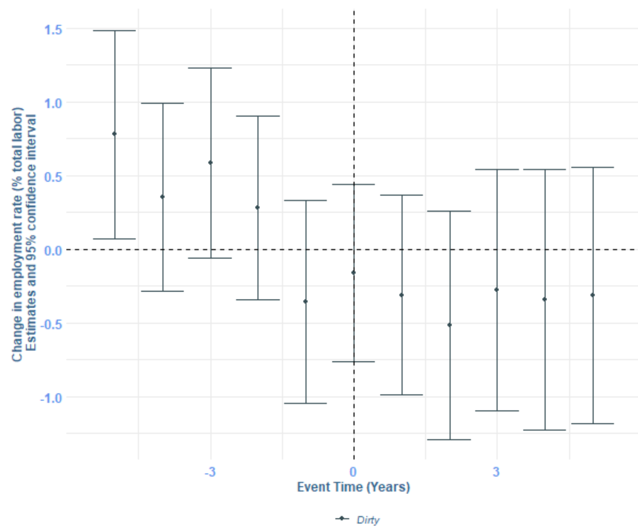


Figure 6 presents the coefficients of the average cumulative effect of the carbon tax on the growth rate in polluting countries, and on the y-axis, in addition to indicating the magnitude, the 95% confidence intervals are presented. It is observed that implementing the carbon tax in countries with a polluting energy matrix is associated with a reduction in the growth rate in the second and third years after 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.

Fig. 7: Employment rate (% of total labor force) in countries with a polluting energy matrix.



Similarly, I estimate the effect of implementing a carbon tax on the employment rate of the countries according to the composition of the energy matrix. Figure **??** shows that the carbon tax is not associated with any effect in the first 5 years, however, from the sixth period onwards, a drop in the employment rate is observed. Although the theoretical model does not explain the effect on employment, this effect can be explained by the fact that the labor force is not sufficiently trained to migrate from the polluting sector to the clean sector, which requires a cost and time of adaptation. The cost of training the skills required for clean production is higher if the share of the polluting sector in final production is predominant. The table 7 shows the estimators and standard error for the countries according to the source of energy generation.

Effect of carbon tax in clean countries. *Corollary 2* implies that introducing a carbon tax favors the annual GDP growth rate in countries with a cleaner than the average energy matrix.

The effects reported in table 5 shows 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 proves the stipulation in Corollary 2 that the higher the initial share of the clean sector in final production, the more positive the effect of the carbon tax becomes. In this case, I approximate the share of the clean sector to the share of clean primary energy sources in final energy consumption.

Fig. 8: GDP growth (%) in countries with clean energy matrix.

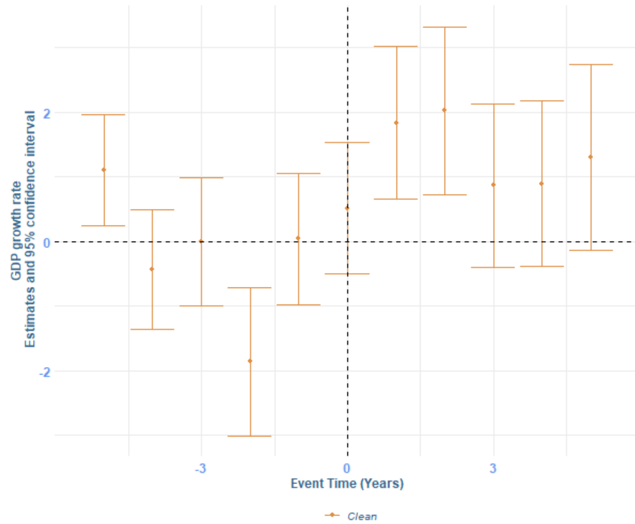
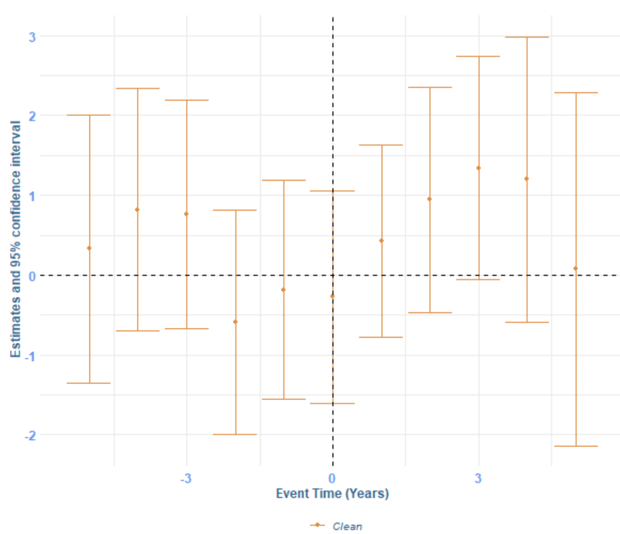


Figure 8 shows that the effect of a carbon tax on the GDP growth rate is positive for countries whose primary energy comes from clean sources. This result suggests that introducing a carbon tax is associated with an increase in annual GDP of 1.4 percentage points in the first 5 years after implementing 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.

On the other hand, as shown in the figure 9, implementing a carbon tax is associated with a slight increase in the employment rate in the third period of implementing the policy, but this effect is not significant.

Fig. 9: Employment rate (percentage of total workforce) in countries with clean energy matrix.



5 Robustness exercises

In order to verify whether the previous results are 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.

Estimates based on different samples of polluting and clean countries For the purpose of determining at what point the effect of the carbon tax on the growth rate ceases to be negative (for polluting countries) and becomes positive. I established different cut-off points Θ based on the percentage of clean energy sources of total energy consumed, i.e., when the sample of polluting countries does not exceed a different percentage of clean energy sources, when the sample of polluting countries does not exceed different percentage of clean energy sources. The results of the effect of the carbon tax on GDP growth, according to the cut-off point of the clean and polluting samples are shown in 10. When the sample of polluting countries does not have even 8% of energy from clean sources (sample of the most polluting countries) the effect is very negative; while when the sample of polluting countries reaches 23% clean energy, the effect is positive. The carbon tax benefits the GDP growth of countries that have at least an energy matrix composed of 17% clean energy.

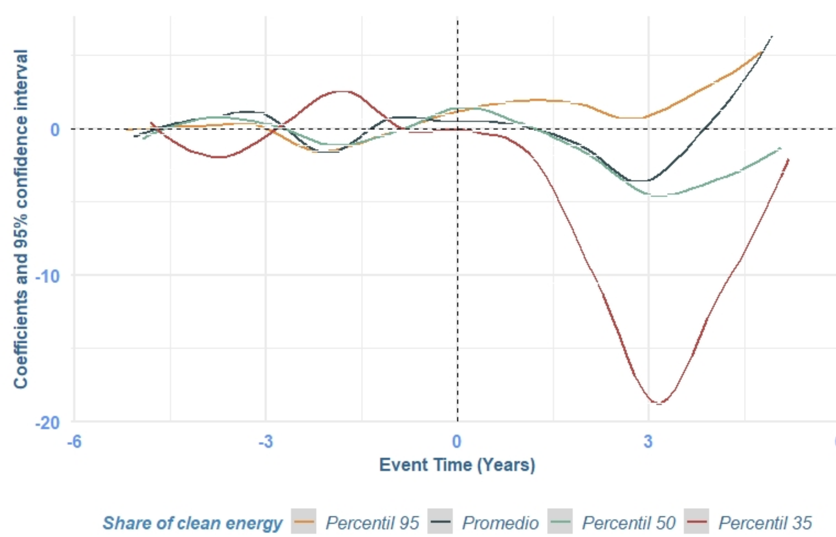
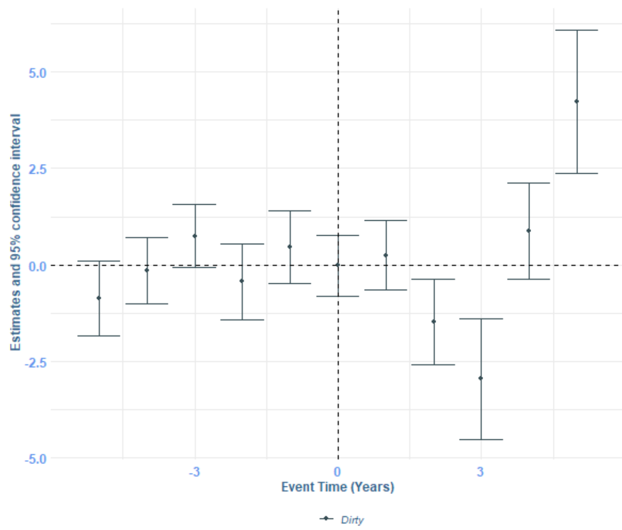


Fig. 10: Effect of the carbon tax at different thresholds of the participation of energy sources.

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.

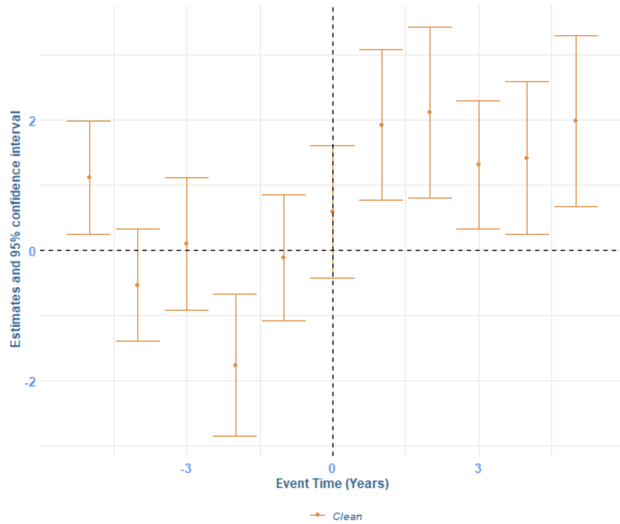
Fig. 11: Effect of carbon tax on GDP growth rate in countries with polluting electricity mix.



The 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 11 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 12 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.

Effect of carbon tax on GDP growth rate at different carbon tax rates. To further explore the relationship between carbon tax and economic growth, I divided the sample into two subgroups based on the level of the carbon tax. I determined this level based on the price of the tax and the percentage of greenhouse gas emissions covered by the tax. I then created two treatment groups: countries with above-average

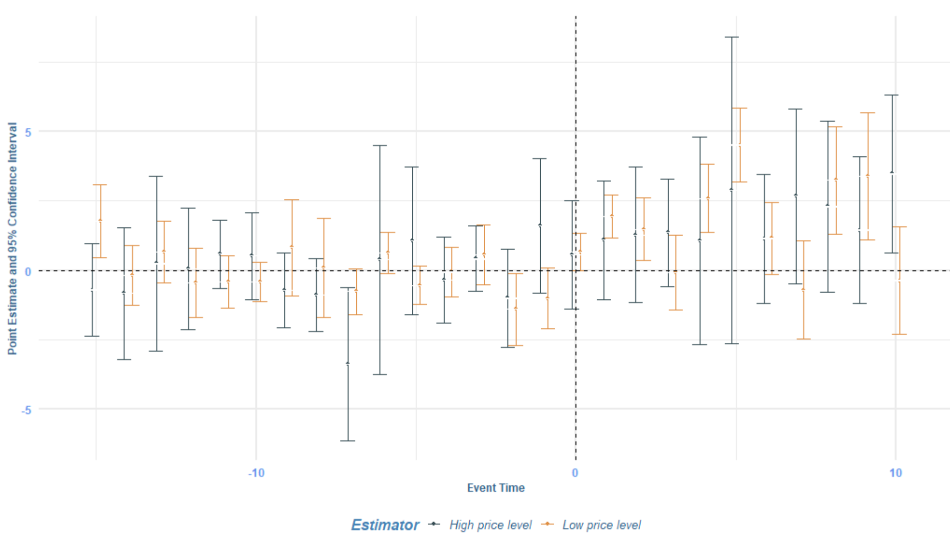
Fig. 12: Effect of carbon tax on GDP growth rate in countries with clean electricity mix.



carbon tax levels and countries with below-average levels.

The analysis revealed that for countries with a lower carbon tax (i.e., lower price and GHG coverage), the growth rate was positive and statistically significant, indicating a positive relationship between cleaner energy and economic growth. However, in countries with a higher carbon tax (i.e., higher price and GHG coverage), the effects were not statistically significant, despite following a similar trend. Figure 13 shows these results.

Fig. 13: Effect of carbon tax on GDP growth rate, depending on the price and coverage of the carbon tax.



6 Conclusions

The findings of the study suggest that the macroeconomic impact of a carbon tax is closely tied to the clean and dirty production in the economy. To measure this, the study used the proportion of energy generated from low and high-carbon intensity sources. In countries where energy production is primarily from high-carbon intensity sources, the implementation of a carbon tax may lead to a short-term slowdown in GDP growth and a long-term reduction in employment rates. This confirms proposition 1 in the theoretical model.

On the other hand, in countries where energy production is primarily sourced from low-carbon intensity sources, the implementation of a carbon tax can boost GDP growth in the short term and have no negative or statistically significant effect on employment.

Furthermore, the study found that the negative impact on GDP growth in high-carbon intensity economies tends to diminish in the long term. This is because the reduced demand for polluting goods encourages innovation in the clean sector, leading to its growth and the eventual surpassing of the polluting sector. As the clean sector grows and becomes dominant, the economy can return to its pre-tax growth trend.

According to the model, a carbon tax increases the cost of producing final goods with dirty or polluting sources, reducing the demand for these goods. As a result, the production of dirty goods tends to decrease, while the productivity of the clean sector improves. Additionally, the carbon tax can increase labor participation in the clean sector, as companies shift towards cleaner production methods to avoid the tax. Overall, the model suggests that a carbon tax can be an effective policy tool for reducing carbon emissions and promoting clean economic growth.

The model highlights the importance of the destination of the tax revenue from the carbon tax. When used to subsidize the production of final goods produced with clean sources, the productivity of the clean sector can be accelerated, boosting economic growth. This can minimize the negative effect of the carbon tax on economic growth.

These findings underscore the importance of considering the energy mix when designing effective climate policies, such as carbon taxes. The greater the proportion of low-carbon intensity sources in energy production, the less harmful the impact of the policy on economic growth, and it may even have a positive effect.

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7 Appendix

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 to 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$)	609238.88	322000.91	721705.56	654034.94	161623.54	1096710.94
GDP growth (annual %)	10.02%	10.17%	0.91%	9.26%	9.44%	1.04%
GDP per capita (current US$)	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$)	1164569.32	579572.91	1359162.31	1302519.86	168376.80	3459270.47
GDP growth (annual %)	9.72%	9.86%	0.95%	9.06%	9.07%	1.19%
GDP per capita (current US$)	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 composition.

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 composition of the countries.

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)