Can we have growth while reducing emissions?

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Abstract. Does the effect of introducing a carbon tax on economic growth and employment differ between countries according to the composition of the energy matrix? To answer this question, I follow a model of directed technical with clean and dirty inputs and study the effects of taxing the production of dirty goods and subsidizing the production of clean goods. I derive four main results: (i) In the absence of subsidies, carbon taxes have a negative effect of economic growth, (ii) this negative effect is a decreasing function of the share of clean goods in total output. (iii) a subsidy to clean goods have a positive effect on economic growth, (iv) and the size of the effect grows with the share of the clean sector. From the previous results it follows that in countries with an energy matrix composed mostly of low-carbon sources a carbon tax whose revenue is used to finance subsidies to the production of clean goods has a positive effect on economic growth while in countries with an energy matrix composed mostly of high-carbon sources a carbon tax whose revenue is used to finance subsidies to the production of clean goods has a negative effect on economic growth. Based on the theoretical model I study the effects of the introduction of a carbon tax using the event study method with a database of 74 countries from the year 1990 to 2020. There are two main empirical results: First, implementing a carbon tax in countries with an energy matrix composed mostly of low-carbon sources generates an increase in the GDP growth rate during the first years after the policy implementation. Second, countries with an energy matrix composed mostly of carbon-intensive sources experience a decrease in the growth rates in the first years after implementing the climate policy; this negative effect disappears in the long term. In addition, in countries with a high share of primary energy from carbon-intensive sources, the carbon tax is associated with a reduction in long-term employment rates.

Keywords: Carbon tax, Directed Technical Change, Climate change and Environment.
JEL Codes: O1,O4, 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, globally and between countries, the trends of the change in CO2 emissions and the change in GDP do not match completely. Some countries have managed to reduce emissions while increasing their GDP. This means that there are additional influences that come into play such as the mix of fuels (energy and carbon intensity).

One of the most widely used 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 matrix 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 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.

This article contributes to the literature in three ways. First, I present a simple 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 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.

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

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. On the other hand, it has been observed that some countries decide to act against climate change based on the composition of their energy matrix.

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.

In the present study, I show theoretically and empirically how the effect of the carbon tax depends on the mix of sources of primary energy consumption. For that purpose, I follow the model of Acemoglu et al. (2012a) that introduces directed technical change in a growth model with environmental restrictions. In this model, the final good is produced by two inputs from two sectors "clean" and "dirty" (according to the energy source consumed), by introducing an environmental policy innovations can be oriented to improve technology in the clean sector. Within this framework, inputs from clean and dirty sources are substitute goods[2]. From the model described above and considering the participation of primary energy sources, I determine the equation for the GDP growth rate based on the carbon tax, revenue recycling, final production, and technology.The effect of introducing a carbon tax on the GDP growth rate is an increasing function of the initial share of clean energy sources, that is, the higher the share of clean energy sources, the more beneficial the effect of the carbon tax on the GDP growth rate (or the negative effect is reduced).

The remainder of the paper is organized as follows. Section II presents the tehoretical 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 Conceptual framework

This section presents a version of the model of Acemoglu et al. (2012a) which introduces an endogenous and directed technical change in a growth model with environmental constraints. Following this model, and taking into account the final production share that uses clean and dirty energy sources, I characterize how the effect of a carbon tax on GDP growth responds to changes in the share of primary energy sources. From the previous specification, I establish a proposition and three corollaries that are testable empirically in Section 3.

2.1 Model: The Environment and Directed Technical Change.[3]

In this model, the final good is produced from “dirty” and “clean” inputs. The authors demonstrate that sustainable growth can be achieved with taxes and/or subsidies that direct innovations toward the clean sector. Each country is inhabited by a continuum of households comprising workers, entrepreneurs and scientists. Households have the following **preferences**:

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

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. We assume that $S_t \in [0, \bar{S}]$,

[2] Assumption based on estimates from work by Papageorgiou et al., 2017 Papageorgiou et al., 2017

[3] the theoretical model closely follows the model of Acemoglu et al., 2012a. The contribution to the model is the equation that allows identifying the effect of the carbon tax on the growth rate, considering the participation of primary energy sources.

where $\bar{S}$ is the quality of the environment absent any human pollution, that is $S_0 = \bar{S}$. In particular, if $S_t = 0$ then there is an environmental disaster. The utility function satisfies the Inada conditions, that is, as consumption approaces to zero its marginal utility goes to infinity. Finally, as environmental quality appoches to zero utility goes to minus infinity. This implies that the environmental quality reaching its lower limit has serious consequences on utility.

There is a unique final or consumption good, Y_t, produced using "clean" and "dirty" inputs (depending on primary energy source required), Y_{ct} y Y_{dt}, according to the **aggregate production function**:

$$Y_t = \left((Y_{ct})^{\frac{\epsilon-1}{\epsilon}} + (Y_{dt})^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{\epsilon}{\epsilon-1}} \tag{2}$$

where $\epsilon \in (0, +\infty)$ is the elasticity of substitution between the two sectors. If the inputs are substitutes, $\epsilon > 1$, then the any production of the final good can be obtained from alternative energies with less pollution. 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 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}. Then, using the final goos as the numeraire, the price of the inputs that the producer of the final good must pay is:

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

where P_{ct} y P_{dt} are the prices of dirty and clean inputs. The relative demand for inputs is:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{ct}}{P_{cd}}\right)^{-\epsilon} \tag{4}$$

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

$$Y_{jt} = (A_{jt}L_{jt})^{1-\alpha}(x_{jt})^{\alpha} \tag{5}$$

where $j \in (c, d)$ denotes the sector, $\alpha \in (0, 1)$, A_{jct} is the quality of machine used in sector j at time t, and xjt is the quantity of this machine.

Following Acemoglu et al. (2012a), we assume that new technologies are produced by scientists and each scientist decides whether to direct her research to clean or dirty technology. She is then randomly allocated to at most one machine and is successful in innovation with probability $\eta_j \in (0, 1)$ in sector $j \in (c, d)$, where innovation increases the quality of a machine by a factor $1 + \gamma$ (with $\gamma > 0$). We 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 **aggregate productivity** in sector j is defined as:

$$A_{jt} = (1 + \gamma \eta_j s_{jt}) A_{jt-1} \tag{6}$$

where A_{dt} corresponds to "dirty technologies," while A_{ct} represents "clean technologies." In this case, the production of the dirty input does not use the exhaustible resource.

Labor is mobile so there are no differential wages. Market clearing for labor requires labor demand to be less than total labor supply, which is normalized to 1, i.e.,

$$L_{ct} + L_{dt} \leq 1 \tag{7}$$

As mentioned above, there are two ways to produce Y_t, where Y_{ct} is the final production made by clean energy and Y_{dt} is the final production made by dirty energy that deteriorates the environment. The equation 8 imposes a limit on the dirty production rate:

$$S_{t+1} = -\xi Y_{dt} + (1 + \rho) S_t \tag{8}$$

The parameter $\xi > 0$ measures the rate of environmental degradation resulting from the production of dirty inputs, and $\rho > 0$ is the rate of "environmental regeneration". Whenever the right hand side is in the interval $(0, \bar{S})$ it is possible the production. On the contrary, whenever the right-hand side is greater than $\bar{S}$, $S_{t+1} = \bar{S}$ no production is possible, as this would imply an environmental disaster, thus the end of any kind of production.

In particular, if $Y_{dt} > \frac{(1+\rho)S_t}{\xi}$ then environmental quality deteriorates year by year until it converges to zero. Therefore, the central objective of environmental policy is to ensure that the production of dirty goods is sufficiently low, given the environmental quality, that is, $Y_{dt} < \frac{(1+\rho)S_t}{\xi}$.

2.2 The *Laissez-Faire* Equilibrium, in autarky

In order to characterize the equilibrium, we have to solve the profit maximization of machine producers, inputs producers and final goods producers as well as the expected profits of reseraches. [4]. Taking into account the probability of successfully innovating η_j in sector $j \in (c, d)$, the relative benefits from conducting research in the clean sector Π_{ct}, relative to the dirty sector Π_{dt}, is therefore:

$$\frac{\Pi_{ct}}{\Pi_{dt}} = \left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}} \times \frac{L_{ct}}{L_{dt}} \times \frac{A_{ct-1}}{A_{dt-1}} \tag{9}$$

The relative benefits of innovating in the clean sector can be explained by three forces:

- *Direct productivity effect* (captured by the term $\frac{A_{ct-1}}{A_{dt-1}}$) The relative benefits of innovating are always greater in the sector with a higher technological level.

[4] see the Annex 7.2 In Annex 7.2 we present the derivation of the equilibrium step by step.

- *Scale Effect* (captured by the term $\frac{L_{ct}}{L_{dt}}$) This effect creates incentives to develop technologies that have a larger market. The greater the employment in a sector, the greater the incentives to innovate and work in it.
- *Price Effect* (captured by the term $\left(\frac{p_{ct}}{p_{dt}}\right)^{\frac{1}{1-\alpha}}$) This effect creates incentives to develop technologies in less advanced sectors because they are more costly (see equation 22).

When no climate policy is implemented, the probability of achieving innovation is higher in the dirty sector, ergo, the dirty sector technology grows faster than the clean sector leading to an environmental disaster in the long term. Suppose the economy starts at date 0 with $S_0 > 0$. We now proceed to examine under what conditions a tax on dirty production could prevent the environmental disaster, and how the growth path of the economy would be affected by such a tax.

2.3 Tax on dirty production

Environmental policies such as a carbon tax (τ_t) or a research subsidy in the clean sector (q_t) play an important role in directing innovations to the clean sector. In this model I assume that the rate of the dirty technology tax and the clean technology subsidy are exactly the same ($\tau_t \cdot Y_{dt} = q_t \cdot Y_{ct}$). The amount collected from the carbon tax is often reinvested in reducing deforestation and incentives to reduce carbon-intensive energy use. Then we could denote the subsidy on clean technology as:

$$q_t = \tau_t \cdot \lambda \tag{10}$$

Where $\lambda_t = \frac{Y_{dt}}{Y_{ct}}$, is the ratio of dirty to clean production. The carbon tax increases the relative demand for clean inputs as the price of each unit produced with dirty inputs increases, and reduces the price of each unit produced with clean inputs. Thus the relative demand for the input will be:

$$\frac{Y_{ct}}{Y_{dt}} = \left(\frac{P_{dt}(1+\tau_t)}{P_{ct}(1-\tau_t \cdot \lambda)}\right)^{\epsilon} \tag{11}$$

On the other hand, if the tax revenue is invested in R&D in the clean sector, it causes the technological level of the clean sector to grow faster than in the polluting sector. The production growth rate for each of the sectors is determined by:

$$g_{ct} = \frac{A_{ct}(1+\tau_t \cdot \lambda_t)^{\frac{1}{1-\alpha}}}{A_{ct-1}} - 1 \tag{12}$$

$$g_{dt} = \frac{A_{dt}(1-\tau_t)^{\frac{1}{1-\alpha}}}{A_{dt-1}} - 1 \tag{13}$$

In order for the tax to discourage innovation in the dirty sector and increase the relative probability of innovating in the clean sector, the tax must meet the following condition:

$$\tau_t \lambda_t > \left(\frac{A_{dt}}{A_{ct}}\right)^{(1-\alpha)(\epsilon-1)-1} \times \frac{1}{(1+\tau_t)^{\epsilon}} - 1 \tag{14}$$

Combining the equation 12, 13, and taking into account the initial share of production of inputs using the equation 2, I establish the equation for the aggregate productivity growth rate $g_t = \frac{\Delta_Y}{Y}$ [5].

$$g_t = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \left(\frac{A_{ct}(1+\tau_t \cdot \lambda_t)^{\frac{1}{1-\alpha}}}{A_{ct-1}}\right) - 1 + \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \left(\frac{A_{dt}(1-\tau_t)^{\frac{1}{1-\alpha}}}{A_{dt-1}}\right) - 1 \tag{15}$$

Equation 15 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* $\frac{Y_{dt}}{Y}$, is not affected by climate policy, but it 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. 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 10 in the Annex.*

Proof The change in the growth rate given the existence of a carbon tax is expressed by the derivative with respect to τ_t:

$$\frac{\partial g_t}{\partial \tau_t} = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{1}{1-\alpha} \cdot \left(\frac{A_{ct}(1+\tau_t \cdot \lambda_t)^{\frac{1}{1-\alpha}-1}}{A_{ct-1}}\right) \cdot \lambda_t - \frac{Y_{dt}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{1}{1-\alpha} \cdot \left(\frac{A_{dt}(1-\tau_t)^{\frac{1}{1-\alpha}-1}}{A_{dt-1}}\right) \tag{16}$$

A notable conclusion from this proposition is that the tax accelerates the productivity of the clean sector and decelerates the productivity of the dirty sector. Thus, depending on the relative share of the sectors in production, the net effect of the carbon tax on economic growth varies. That is, if the share of dirty inputs in production is higher than a critical level relative to clean production, the effect of introducing a carbon tax on the growth rate of the economy may be negative.

A notable conclusion from this proposition is that the tax accelerates the productivity of the clean sector and decelerates the productivity of the dirty sector. Thus, depending on the relative share of the sectors in production, the net effect of the carbon tax on economic growth varies. That is, if the share of dirty inputs in production

[5] the detailed procedure is in Anexo 7.2

is higher than a critical level relative to clean production, the effect of introducing a carbon tax on the growth rate of the economy may be negative. Thus, if the share of clean input production is greater than a critical level, the effect of the carbon tax may be positive.

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,* $Y_{ct} < \lambda < Y_{dt}$*, 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,* $Y_{ct} > \lambda > Y_{dt}$*, 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 74 countries, of which 23 had implemented a carbon tax. The sample covers the period from 1990 to 2020.

Information on countries that have implemented a carbon tax[6] was obtained from the World Bank's Carbon Pricing Dashboard database: https://carbonpricingdashboard.worldbank.org/map_data. The carbon tax sets an explicit price on GHG emissions expressed as a value per ton of carbon dioxide equivalent (tCO2e), which is determined by each country that ccan be between US$2/tCO2e and US$137/tCO2e. The sectors covered by the tax are generally industry, transportation, construction, and power generation, in addition to fossil fuels. In most countries the tax is levied on distributors and importers, followed by fossil fuel users, and a minority of countries levy it on producers. Table 2 in the annex presents in detail the characteristics of the carbon tax for each of the countries studied.

Figure 1 shows the cumulative number of countries that have implemented a carbon tax from 1990 to 2020. It can be seen that since 2010 the adoption of carbon taxes in the countries has increased. In recent years countries such as Uruguay, Senegal, Ivory Coast, Indonesia, and Austria are considering implementing a carbon tax.

[6] variables like year of implementation, price, and GHG emissions coverage.

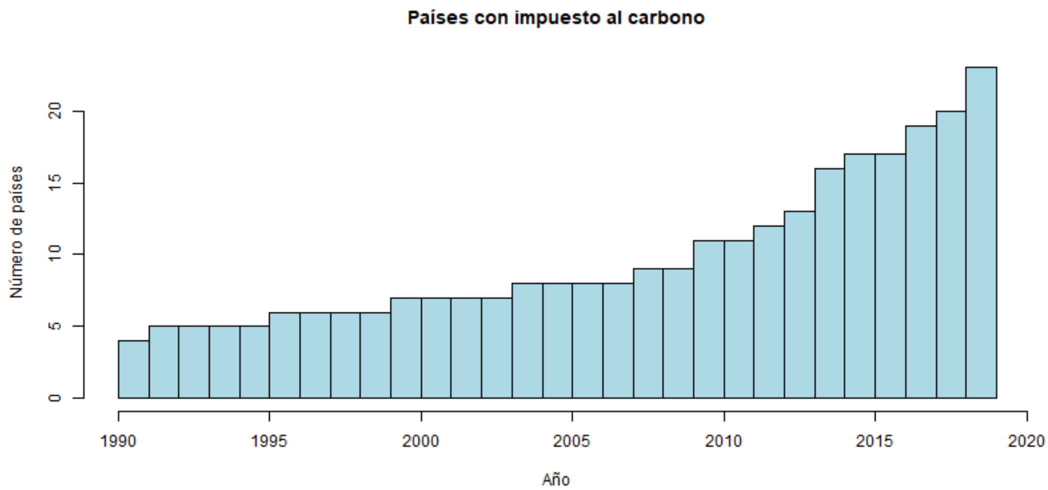


Fig. 1: Number of countries that implemented a carbon tax per year.

Table 1 presents descriptive statistics of the variables of interest and the sources of the databases. The outcome variables studied are GDP growth (% per year) and the employment rate measured as number of employees over economically active population (% of total active population). These variables were obtained from the World Bank's development indicators table. [7].

Table 1: Description of the main outcome variables.

Variable	Mean	Median	Std. Dev.	Source
Real GDP at constant domestic prices (millions 2017US$)	1026887	258975	2511953	Penn World Table
Crecimiento del PIB (anual %)	2.86%	2.99%	4.33%	Data WorldBank
GDP per capita (current US$)	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%	Our World in Data.
Clean electricity fraction* (% total consumption)	37%	32%	31%	Our World in Data.
Countries	74			
Observations	2511			

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

Data on primary energy consumption (TWh) by source are from Our World in Data[8]. The share of primary energy consumed by source was used to divide the samples into countries with a polluting "dirty" and low-polluting "clean" energy matrix. The share of total primary energy was calculated by Our World in Data based on the "substitution method", taking each source's share of primary energy from all sources normalized to exajoules (EJ); this takes into account inefficiencies in fossil fuel production and is a better approximation of the "final energy" consumed. In the Annex 11

[7] available at https://datos.bancomundial.org/
[8] available at: {https://n9.cl/b85gh

I present Colombia's energy balance, which is an aggregate representation of the total energy consumed by sector and the participation of each of the primary sources.

The sum of hydro, nuclear, solar and wind energy consumption constitute the "clean" energy sources. The sum of energy consumption generated by the combustion of fossil fuels such as coal, oil, natural gas and biofuels constitute the "dirty" energy sources. The consumption of clean and dirty energy is divided by the total primary energy consumption of each country and each year, thus determining the share of energy from clean and dirty sources in the final energy consumption. 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 "clean" 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 "dirty" energy matrix. The figure shows the share of energy from "clean" sources of the countries, in which 25 countries had introduced a carbon tax by 2020.

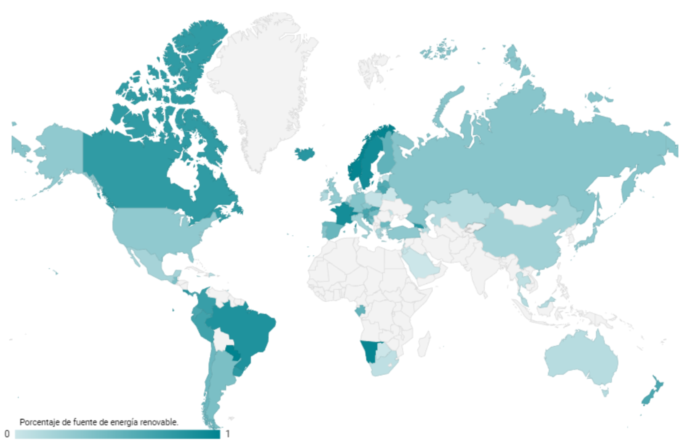


Fig. 2: Map of countries according to primary energy share

The table 3 presents the statistics of the outcome variables for each sample, the full sample of 74 countries, and the sample of countries with a clean and dirty energy matrix.

In order to empirically analyze the corollaries, I use the share of primary energy sources in final energy consumption as a proxy for the initial share of clean and dirty sectors in the final production, represented in the theoretical model as $\frac{Y_{ct}}{Y}$ and y $\frac{Y_{dt}}{Y}$.

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). I further divide the database into two subsamples according to energy matrix composition.

Countries with an energy matrix composed of more than 14% of clean energy sources (such as hydro, nuclear, solar and wind) belong to the subsample of "clean countries". In the theoretical model this subsample tests corollary 2, where there is a large share of the clean sector in final production at the time the tax is implemented, $Y_{ct} > \lambda > Y_{dt}$. Similarly, countries with an energy matrix composed of more than 86% of polluting sources (such as coal, oil, natural gas and biofuels) make up the subsample of "dirty countries". This subsample is associated with corollary 1, in which there is a large initial share of the dirty sector in the final production, $Y_{ct} < \lambda < Y_{dt}$.

The dynamic difference-in-difference (DiD) strategy, also called 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. We 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).

Effect of a carbon tax in countries with dirty primary 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 dirty sector in final output is greater than a critical level relative to the share of the clean sector, $Y_{ct} < \lambda < Y_{dt}$. To test this empirically we use the empirical event study strategy and the subsample of "dirty countries", consisting of those countries whose share of clean sources is below the average.

In this model I assume as year 0 the year in which the carbon tax was introduced, from this year onwards I enumerate the periods before ($t < 0$) and after ($t > 0$) and equalize time t=0 for all countries in the treatment group. Assuming that the evolution of the potential outcome in the absence of the treatment decomposes additively into a time fixed effect, I estimate the average dynamic effect of introducing a carbon tax on GDP and employment growth $Y_{c,t}$ in country c and year t. The equation 17 is employed in the analysis:

$$Y_{c,t} = \beta_1 \sum_{-T \leq r \leq T}^{r \neq 0} 1\left[CarbonTax_{c,t} = r\right] + \Phi_c + \Phi_t + \epsilon_{c,t} \tag{17}$$

where $Y_{c,t}$ is the GDP growth rate and employment rate. β_1 measures the average dynamic effect of climate policy, in the sample of "dirty countries". When the outcome variable is the economic growth rate this estimator tests the *corollary 1*. Also include α_c ecountry 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 clean primary 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 dirty sector, $Y_{ct} > \lambda > Y_{dt}$. To empirically test corollary 2 we 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 18 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.

$$Y_{c,t} = \beta_1 \sum_{-T \leq r \leq T}^{r \neq 0} 1\left[CarbonTax_{c,t} = r\right] + \Phi_c + \Phi_t + \epsilon_{c,t} \tag{18}$$

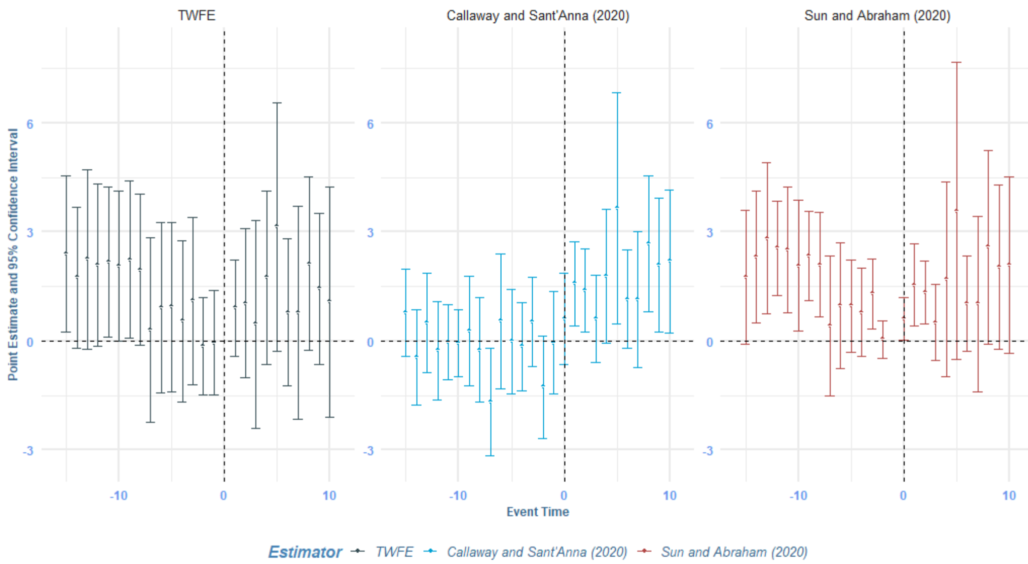
$Y_{c,t}$ is the GDP growth rate and employment rate. β_1 measures the average dynamic effect of climate policy, in the sample of "clean countries". When the outcome variable is the economic growth rate this estimator tests the *corollary 2*. I include α_c country fixed effects c for unobserved country-specific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

4 Results

4.1 Effect of carbon tax on growth rate and employment

Figure 3 presents the effect of implementing a carbon tax on the annual GDP growth rate using the database of 74 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. 3: 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. 4: Effect of the carbon tax on employment rate.

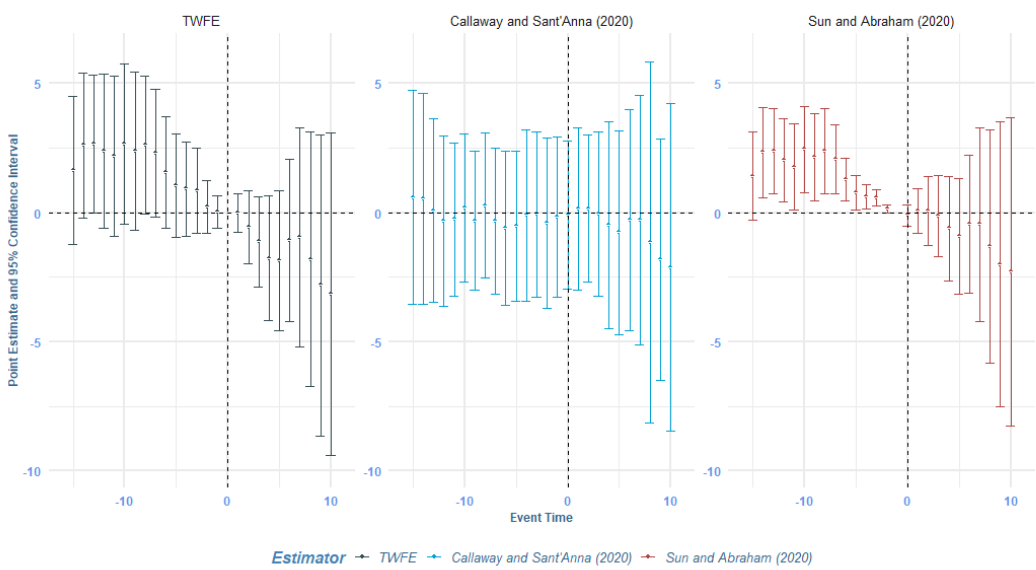


Figure 4 presents the results of the effect of the carbon tax on the employment rate using the whole sample. There is evidence of a decrease in the employment rate after the third and fourth year, but there is no statistical significance in any of the estimators 5. It could be argued that the carbon 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 dirty sources as a proxy for the initial share of the clean and dirty 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 dirty 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. 5: Annual GDP growth (%) in countries with a polluting energy matrix.

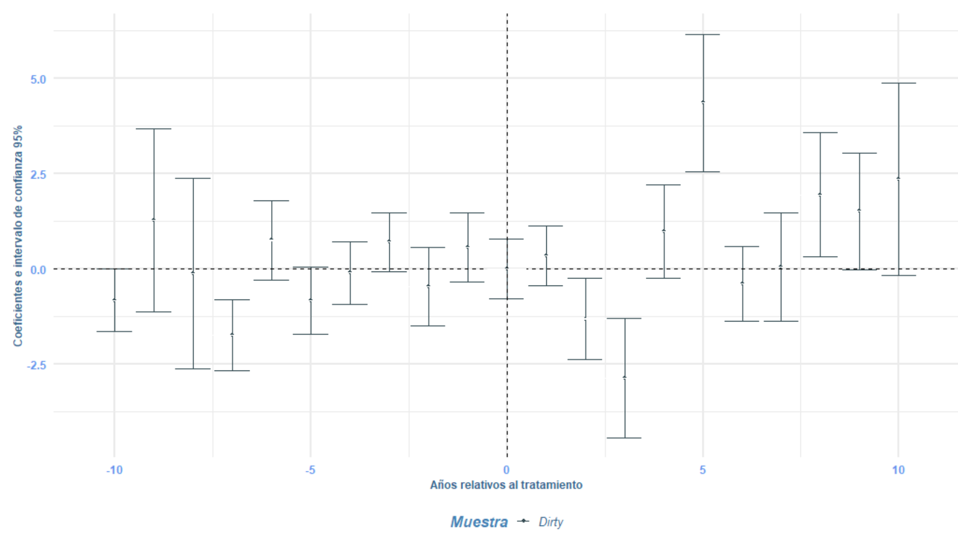
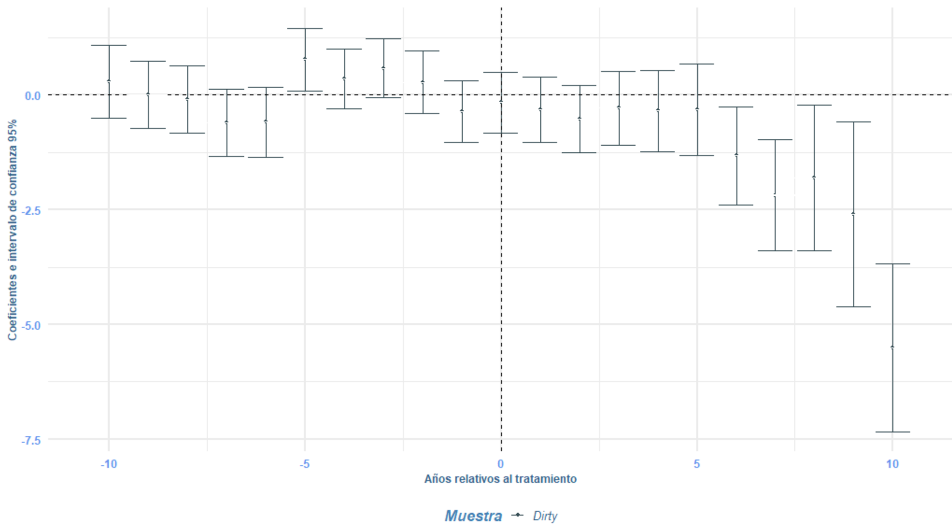


Figure 5 presents the coefficients of the average cumulative effect of the carbon tax on the growth rate in polluting countries, and on the y-axis, in addition to indicating the magnitude, the 95% confidence intervals are presented. It is observed that implementing the carbon tax in countries with a polluting energy matrix is associated with a reduction in the growth rate in the second and third years 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. 6: 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 dirty 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 6 shows the estimators for countries with a clean and dirty 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, we approximate the share of the clean sector to the share of clean primary energy sources in final energy consumption.

Fig. 7: GDP growth (%) in countries with clean energy matrix.

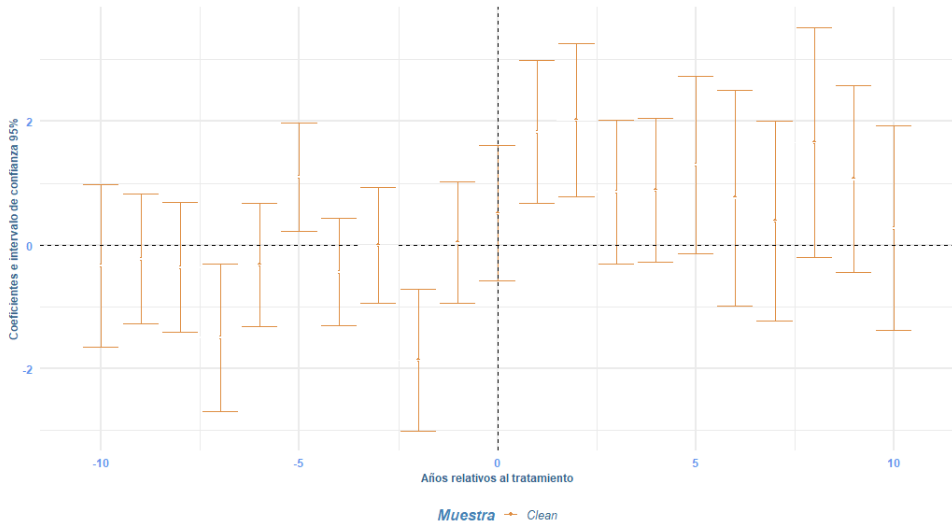
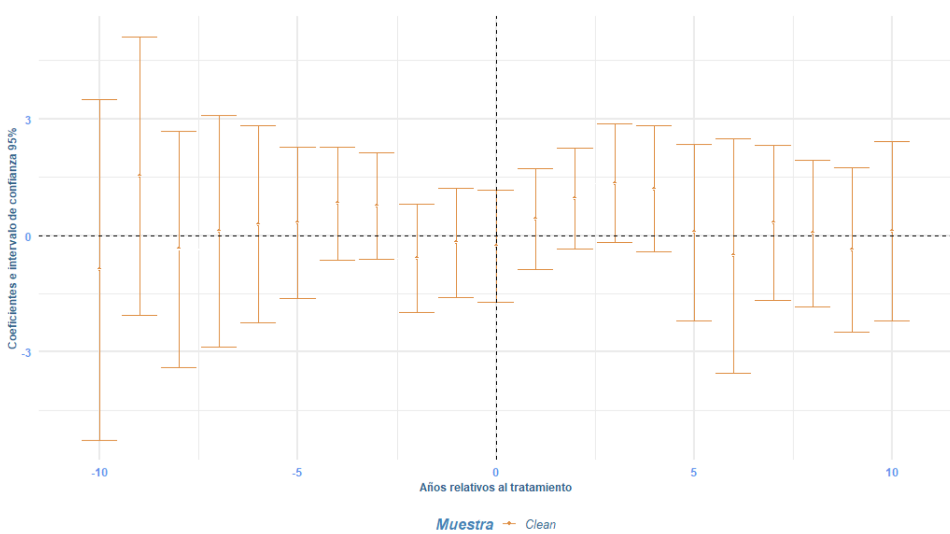


Figure 7 shows that the effect of a carbon tax on the GDP growth rate is positive for countries whose primary energy comes from clean sources. This result suggests that introducing a carbon tax is associated with an increase in annual GDP of 1.4 percentage points in the first 5 years after implementing 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 8, 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. 8: 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 dirty and clean countries, based on the thresholds of the share of energy sources Ṡecond, I used the sources of electricity generation, in exchange for the energy matrix, as they can approximate the share of the sectors (clean and dirty) in the final production.

For the purpose of determining at what point the effect of the carbon tax on the growth rate ceases to be negative (for dirty countries) and becomes positive. I established different cut-off points λ based on the percentage of clean energy sources of total energy consumed, i.e., when the sample of dirty countries does not exceed a different percentage of clean energy sources, when the sample of dirty 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 dirty samples are shown in 9. When the sample of dirty 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 dirty 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.

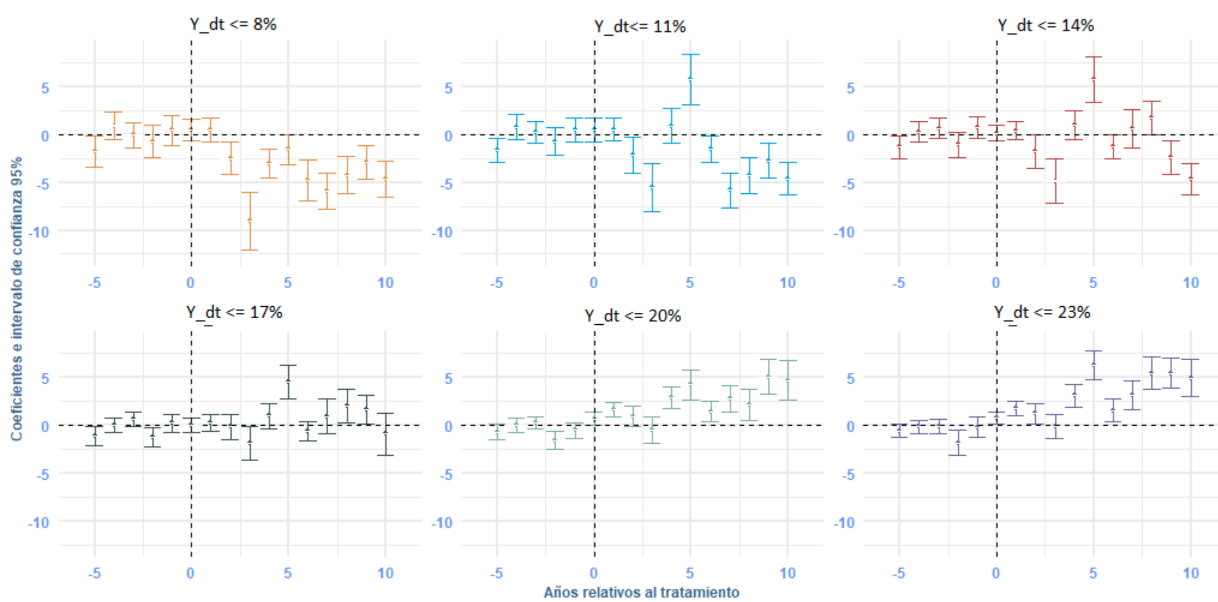


Fig. 9: Effect of the carbon tax at different thresholds of the participation of energy sources.

The electricity matrix 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 dirty 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.

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 12 presents the coefficients of the effect of the carbon tax on the growth rate using the sample of countries with a dirty 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 13 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.

In addition, I estimated the effect on GDP using two subsamples with different levels of carbon tax. The measure of carbon tax level was determined according to the amount of GHG covered by the carbon tax and the price of the tax. I then established two treatment groups, those countries that were above average and below average. Figure 14 shows that in the countries that implemented a lower tax (lower price and GHG coverage) the growth rate is positive and significant and resembles the behavior of countries with a cleaner energy matrix. While in the case of countries with a higher price and GHG coverage tax, the effects follow the same trend but are not significant.

6 Conclusions

The results suggest that the macroeconomic effect of a carbon tax depends on the relative share of clean and dirty production when implementing a climate policy. As a proxy for the relative share of sector production, I use the proportion of energy generated by clean and dirty sources. Thus, in countries whose energy matrix comes mostly from carbon intensity sources, the effect of implementing a carbon tax is associated with a slowdown in the GDP growth rate in the short term and a reduction in the employment rate in the long term. This effect confirms proposition 1, derived from the model of Acemaglu et. al. Acemoglu et al., 2012a.

Second, in countries whose energy matrix comes mostly from clean, low-polluting sources, implementing a carbon tax favors the GDP growth rate in the short term and does not have a negative or statistically significant effect on employment.

It was shown that the negative effect on GDP growth in countries with a dirty energy matrix disappears in the long term. This effect is due to the fact that as the demand for dirty goods is reduced and innovations in this sector decrease, innovations in the clean sector increase, once the growth of the clean sector surpasses the dirty sector, the growth rate of the economy returns to the trend of before implementing the tax.

When designing and implementing climate policies such as the carbon tax, it is important to take into account the composition of the energy matrix, so that the greater the participation of clean sources in energy production, the more the harmful effect of the climate policy on economic growth is minimized, and this effect can even be positive.

7 Appendix

7.1 Solving for the Laissez-Faire Equilibrium

The representative producer of inputs seeks to maximize his profits by choosing the optimal quantities of machines in his sector and the labor demanded.

$$\max_{x_{jt},L_{jt}} P_{it}\left((A_{jt}L_{jt})^{1-\alpha}(x_{jt})^{\alpha}\right) - w_{jt}L_{jt} - p_{jt}xjt \tag{19}$$

where w_{it} is the wage paid for each unit of labor hired in each sector and p_{it} is the price that the producer of inputs must pay for each machine used. From the first-order conditions is obtained the following iso-elastic inverse demand curve:

$$x_{jt} = \left(\frac{\alpha P_{jt}}{p_{jt}}\right)^{\frac{1}{1-\alpha}} A_{jt}L_{jt} \tag{20}$$

The monopolist producer of machine in sector j chooses p_{jt} and x_{jt} to maximize profits $\pi_{jt} = (p_{jt} - \varphi)x_{jt}$, subject to the inverse demand curve. Given this isoelastic demand, the profit-maximizing price is a constant markup over marginal cost, thus $p_{jt} = \frac{\varphi}{\alpha}$. For simplicity Acemoglu et al., 2012a assumed that $\varphi = \alpha^2$, the definition of $\varphi \equiv (1-\alpha)\times(1-\epsilon)$. But in the case when the two inputs are strong substitutes $\epsilon \geq 1/(1-\alpha)$, so, $\varphi \equiv (1-\alpha)$ Then, each monopolist sets a price that supplies the demand of the market $p_{jt} = \alpha$ and thus the equilibrium demand for machines in sector j is obtained as:

$$x_{jt} = p_{jt}^{\frac{1}{1-\alpha}} A_{jt}L_{jt} \tag{21}$$

The equilibrium profits of machine producers can be written as:

$$\pi_{jt} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} A_{jt}L_{jt} \tag{22}$$

Based on the maximization of expected net benefits, the entrepreneur seeks to maximize his probability of achieving an innovation. Then, the probability of innovating in each sector is:

$$\eta_{jt} = \frac{\pi_{jt}}{A_{jt-1}} = (1-\alpha)\alpha p_{jt}^{\frac{1}{1-\alpha}} L_{jt} \tag{23}$$

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

$$\frac{\eta_{ct}}{\eta_{dt}} = \left(\frac{P_{ct}}{P_{dt}}\right)^{\frac{1}{1-\alpha}} \times \left(\frac{L_{ct}}{L_{dt}}\right) \tag{24}$$

From this equation are obtained the relative benefits of innovating 9 and the three forces that determine the relative growth of innovations.

7.2 The aggregate productivity growth rate.

Environmental policy must ensure that the demand for dirty inputs takes into account the environmental cost of an additional unit of the dirty input, $\theta_t = f(\xi)$ (evaluated in terms of units of the final good at time t; recall that one unit of dirty production at time t destroys ξ units of environmental quality at time $t+1$), which is equivalent to a tax:

$$\tau_t = \frac{\theta_t}{P_{dt}} \tag{25}$$

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

$$\left(Y_{dt}^{\frac{\epsilon-1}{\epsilon}} + Y_{ct}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{1}{\epsilon-1}} \times Y_{dt}^{\frac{1}{\epsilon-1}} = P_{dt}(1+\tau_t) \tag{26}$$

$$\left(Y_{dt}^{\frac{\epsilon-1}{\epsilon}} + Y_{ct}^{\frac{\epsilon-1}{\epsilon}}\right)^{\frac{1}{\epsilon-1}} \times Y_{ct}^{\frac{1}{\epsilon-1}} = P_{ct}(1-q_t) \tag{27}$$

In order to measure the change in output growth, we start from the aggregate production function 2:

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

So, the derivative of dirty and clean production are:

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

$$\frac{\partial Y_t}{\partial Y_{ct}} = \left(\frac{Y_t}{Y_{ct}}\right)^{\frac{\epsilon-1}{\epsilon}} \tag{30}$$

Combining the equations 28, 29 and 30 and dividing by Y, we get:

$$\frac{\partial Y_t}{\partial Y_{ct}} = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\partial Y_{dt}}{Y_{dt}} + \frac{Y_{dt}}{Y_{dt}}^{\frac{\epsilon-1}{\epsilon}} \cdot \frac{\partial Y_{ct}}{Y_{ct}} \tag{31}$$

$$\frac{\partial Y_t}{\partial Y_{ct}} = \frac{Y_{ct}}{Y}^{\frac{\epsilon-1}{\epsilon}} \cdot g_{dt} + \frac{Y_{dt}}{Y_{dt}}^{\frac{\epsilon-1}{\epsilon}} \cdot g_{ct} \tag{32}$$

Can positive growth still be sustained in that case? From the Schumpeterian model we know that the economic growth rate is the proportional growth rate of the productivity parameter A_t:

$$g_t = \frac{A_t - A_{t-1}}{A_{t-1}} \tag{33}$$

7.3 Carbon tax and clean technology subsidy

The rate of the clean technology subsidy is exactly equal to the rate of the carbon tax. Therefore, the clean technology subsidy is proportional to the carbon tax rate for the ratio between the production that uses dirty and clean inputs, $q_t = \tau_t \cdot \frac{Y_{dt}}{Y_{ct}} = \tau_t \cdot \lambda_t$. The relative probabilities of innovating in the clean sector, taking into account the taxes and subsidies proposed, are as follows:

$$\frac{\mu_{ct}}{\mu_{dt}} = \left(\frac{A_{ct}}{A_{dt}}\right)^{(1-\alpha)(\epsilon-1)-1} \times \frac{(1+\tau_t)^{\epsilon}}{1-\lambda\tau_t} \tag{34}$$

The tax that makes the probability of innovating in the clean sector higher than in the dirty sector is:

$$\frac{1-\lambda\tau_t}{1+\tau_t} > \left(\frac{A_{ct}}{A_{dt}}\right)^{(1-\alpha)(\epsilon-1)-1} \tag{35}$$

Equation 36 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, λ_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.

$$q_t = \lambda\tau_t > 1 - \left(\frac{A_{ct}}{A_{dt}}\right)^{(1-\alpha)(\epsilon-1)-1} \times (1+\tau_t)^{\epsilon} \tag{36}$$

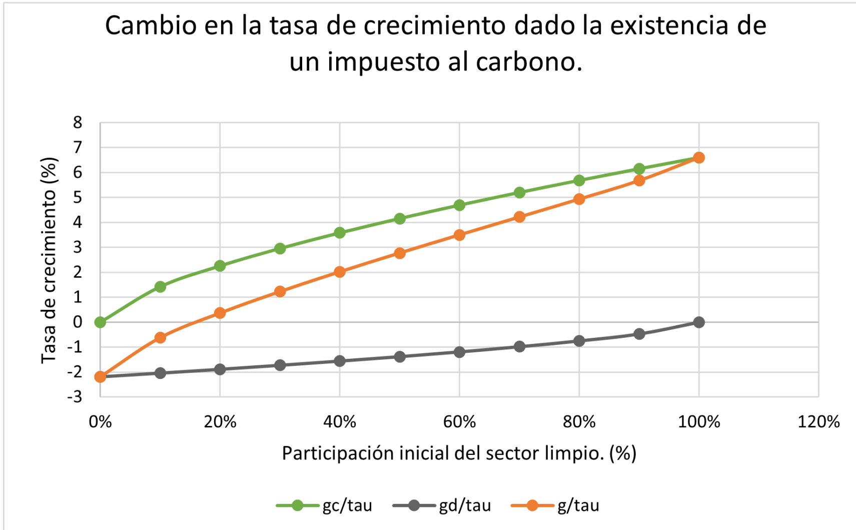


Fig. 10: Graphic representation of the effect of the carbon tax on the growth rate (g_t/τ), according to the initial share of clean inputs in total production. The parameter were calibrated following the values confuration used in Acemoglu et al., 2012a: $\alpha = 0.5$, $\epsilon = 3$, $\tau = 2$.

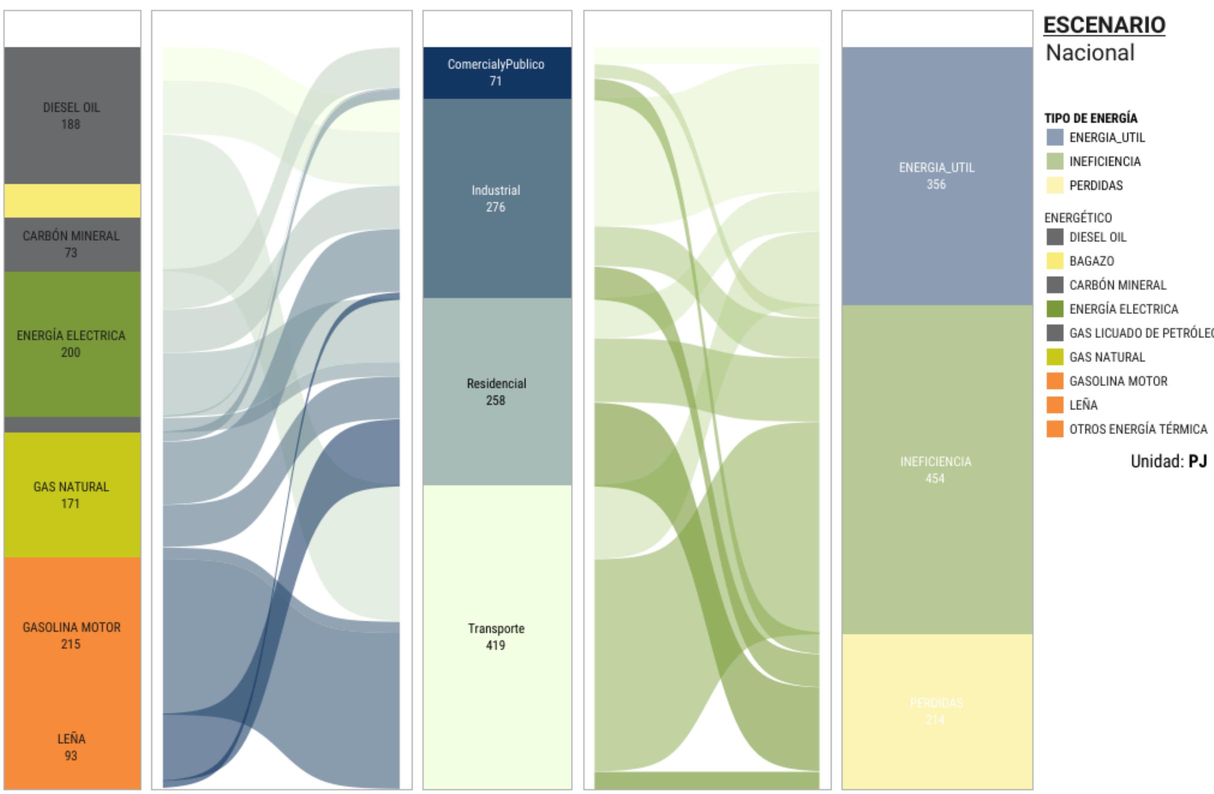


Fig. 11: Sankey diagrams of the Colombian energy sector.

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

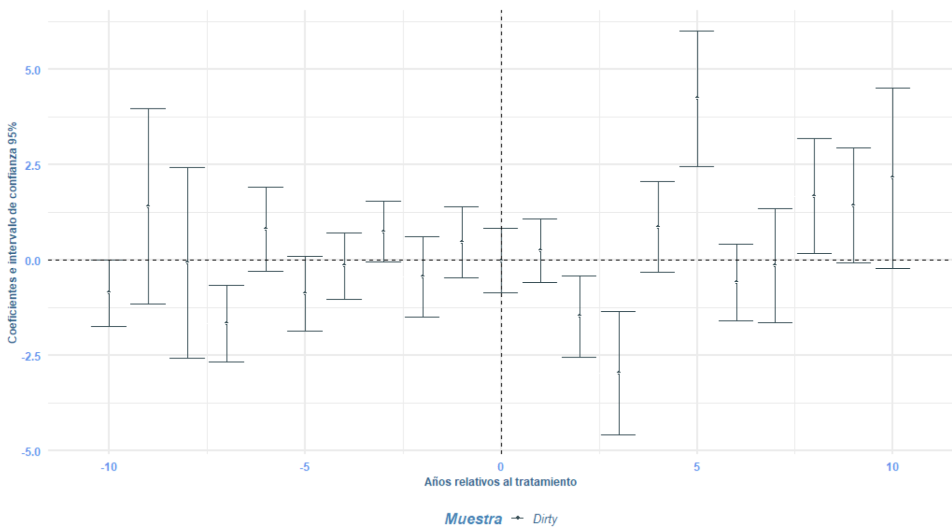


Fig. 13: Effect of carbon tax on GDP growth rate in countries with a low-polluting electricity matrix.

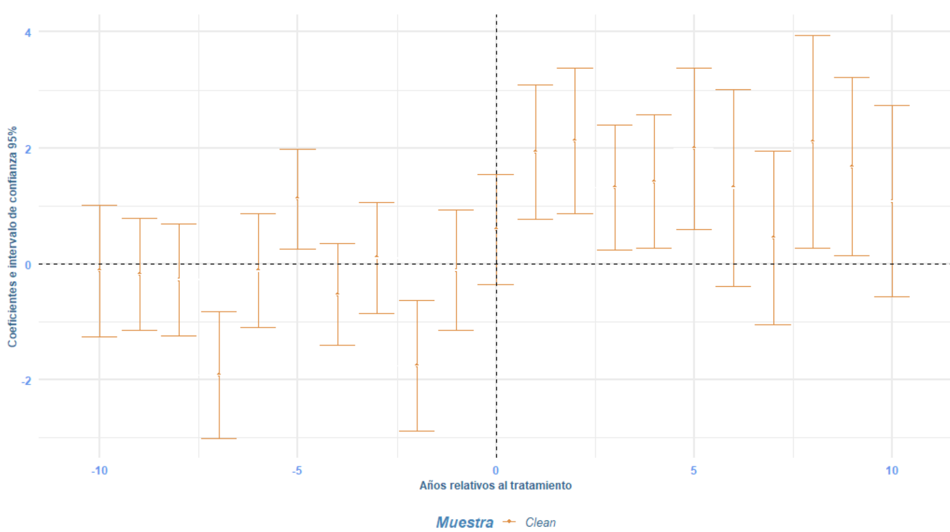
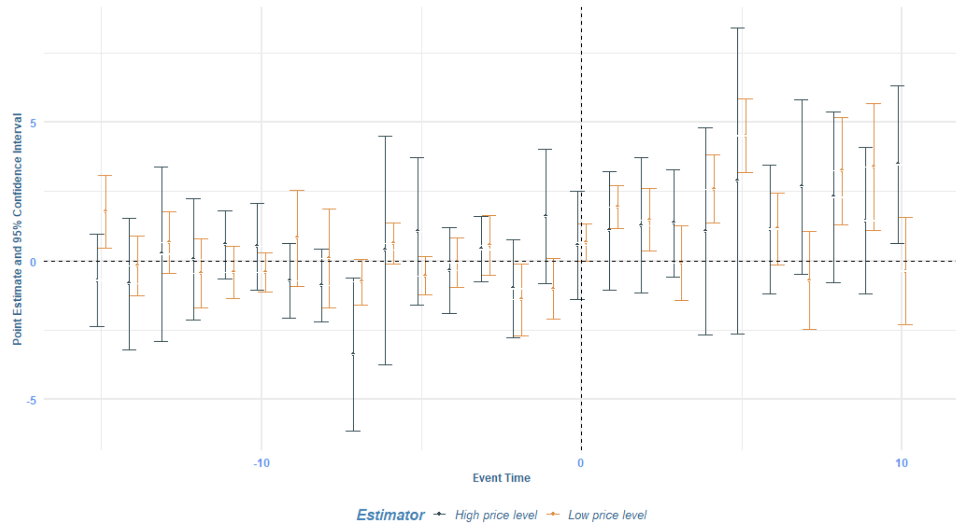


Fig. 14: Effect of carbon tax on GDP growth rate, depending on the price and coverage of the carbon tax.



References

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012a). The environment and directed technical change. *American Economic Review*, *102*(1), 131–66. https://doi.org/10.1257/aer.102.1.131

Acemoglu, D., Aghion, P., Bursztyn, L., & Hemous, D. (2012b). The environment and directed technical change. *The American Economic Review*, *102*(1), 131–166. Retrieved April 15, 2022, from http://www.jstor.org/stable/41408771

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Reenen, J. (2012). Carbon taxes, path dependency and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, *124*. https://doi.org/10.2139/ssrn.2184830

Andersson J, A. G. (2017). *The distributional effects of a carbon tax: The role of income inequality.*

Bernard, J.-T., Islam, M., & Kichian, M. (2018). *Effects of B.C.'s Carbon Tax on GDP* (Working Papers 1812E). University of Ottawa, Department of Economics. https://ideas.repec.org/p/ott/wpaper/1812e.html

Bushnell, J. B., Chong, H., & Mansur, E. T. (2013). Profiting from regulation: Evidence from the european carbon market. *American Economic Journal: Economic Policy*, *5*(4), 78–106. https://doi.org/10.1257/pol.5.4.78

Callaway, B., & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods [Themed Issue: Treatment Effect 1]. *Journal of Econometrics*, *225*(2), 200–230. https://doi.org/https://doi.org/10.1016/j.jeconom.2020.12.001

Delmotte, M. (2021). *Climate change 2021: The physical science basis*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/#SPM

Fan, Y., Jia, J.-J., Wang, X., & Xu, J.-H. (2017). What policy adjustments in the eu ets truly affected the carbon prices? *Energy Policy*, *103*, 145–164. https://doi.org/https://doi.org/10.1016/j.enpol.2017.01.008

Golosov, M., Hassler, J., Krusell, P., & Tsyvinski, A. (2011). *Optimal taxes on fossil fuel in general equilibrium* (CEPR Discussion Papers No. 8527). C.E.P.R. Discussion Papers. https://ideas.repec.org/p/cpr/ceprdp/8527.html

Laffont, J.-J., & Martimort, D. (2009). The theory of incentives: The principal-agent model. *The Theory of Incentives: The Principal-Agent Model*, 1–421.

Mansanet-Bataller, M., & Pardo, A. (2009). Impacts of regulatory announcements on co2 prices. *The Journal of Energy Markets*, *2*(2), 1–33.

Matsumoto, S. (2022). How will a carbon tax affect household energy source combination? *Energy Strategy Reviews*, *40*, 100823. https://doi.org/https://doi.org/10.1016/j.esr.2022.100823

Metcalf, G. E., & Stock, J. H. (2020). Measuring the macroeconomic impact of carbon taxes. *AEA Papers and Proceedings*, *110*, 101–06. https://doi.org/10.1257/pandp.20201081

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: Sampling balance

Variable	Media	Mediana	Desv. Estándar	Media	Mediana	Desv. Estándar
	Panel todos los datos					
	Con impuesto al carbono			Sin impuesto al carbono		
PIB real (millions 2017US$)	850686.90	393482.88	1082446.42	1121275.39	166135.61	3006622.00
PIB per cápita (current US$)	9.89%	10.10%	0.94%	9.11%	9.15%	1.15%
Crecimiento del PIB (anual %)	2.482	2.683	3.694	3.058	3.254	4.630
Tasa de empleo (% total labor)	92.07%	92.85%	4.75%	92.43%	93.02%	4.45%
Consumo de energía primaria (TWh)	1094.63	474.96	1379.31	1855.63	254.93	5334.58
Fracción de electricidad limpia (% total consumo)	47%	46%	33%	31%	24%	29%
Fracción de energía limpia (% total consumo)	23%	18%	20%	9%	4%	11%
Países	23			51		
	Panel - Países con matriz energética relativamente 'limpia'					
	Con impuesto al carbono			Sin impuesto al carbono		
PIB real (millions 2017US$)	609238.88	322000.91	721705.56	654034.94	161623.54	1096710.94
Crecimiento del PIB (anual %)	10.02%	10.17%	0.91%	9.26%	9.44%	1.04%
PIB per cápita (current US$)	2.17	2.57	3.28	2.35	2.67	3.47
Tasa de empleo (% total labor)	92.14%	92.70%	4.51%	90.99%	91.68%	4.23%
Consumo de energía primaria (TWh)	841.80	351.14	1103.98	748.81	232.82	1166.34
Fracción de energía limpia (% total consumo)	70%	71%	21%	60%	60%	16%
Fracción de electricidad limpia (% total consumo)	36%	32%	17%	23%	23%	8%
Países	13			12		
	Panel - Países con matriz energética relativamente 'sucia'					
	Con impuesto al carbono			Sin impuesto al carbono		
PIB real (millions 2017US$)	1164569.32	579572.91	1359162.31	1302519.86	168376.80	3459270.47
Crecimiento del PIB (anual %)	9.72%	9.86%	0.95%	9.06%	9.07%	1.19%
PIB per cápita (current US$)	2.89	2.83	4.14	3.33	3.57	4.98
Tasa de empleo (% total labor)	91.97%	93.96%	5.06%	93.06%	93.67%	4.39%
Consumo de energía primaria (TWh)	1423.29	1010.65	1614.45	2289.49	277.86	6198.64
Fracción de energía limpia (% total consumo)	16%	12%	15%	19%	10%	24%
Fracción de electricidad limpia (% total consumo)	6%	5%	6%	3%	1%	5%
Países	10			49		

Mueller, K.-U., & Steiner, V. (n.d.). Distributional Effects of a Minimum Wage in a Welfare State – The Case of Germany. *SOEPpaper No. 617*. http://dx.doi.org/10.2139/ssrn.2385893

Nordhaus, W. D. (1991). To slow or not to slow: The economics of the greenhouse effect. *The Economic Journal*, *101*(407), 920–937. http://www.jstor.org/stable/2233864

Nordhaus, W. D. (1993). Reflections on the economics of climate change. *Journal of Economic Perspectives*, *7*(4), 11–25. https://doi.org/10.1257/jep.7.4.11

Papageorgiou, C., Saam, M., & Schulte, P. (2017). Substitution between Clean and Dirty Energy Inputs: A Macroeconomic Perspective. *The Review of Economics and Statistics*, *99*(2), 281–290. https://ideas.repec.org/a/tpr/restat/v99y2017i2p281-290.html

Pearce, D. (1991). The Role of Carbon Taxes in Adjusting to Global Warming. *The Economic Journal*, *101*(407), 938–948. https://doi.org/10.2307/2233865

Popp, D. (2002). Induced innovation and energy prices. *American Economic Review*, *92*(1), 160–180. https://doi.org/10.1257/000282802760015658

Rausch, S., Metcalf, G. E., & Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households [Supplemental Issue: Fourth Atlantic Workshop in Energy and Environmental Economics]. *Energy Economics*, *33*, S20–S33. https://doi.org/https://doi.org/10.1016/j.eneco.2011.07.023

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

Rodríguez, X. B. y. C. G., Manuel Henry Mance. (2015). *Cambio climático: Lo que está en juego*. WWF, Uniandes, Friedrich Ebert Foundation y FNA. https://library.fes.de/pdf-files/bueros/kolumbien/12047.pdf

Romer, C. D., & Romer, D. H. (2010). The macroeconomic effects of tax changes: Estimates based on a new measure of fiscal shocks. *American Economic Review*, *100*(3), 763–801. https://doi.org/10.1257/aer.100.3.763

Stern, N. (2007). *The economics of climate change: The stern review*. Cambridge University Press. https://doi.org/10.1017/CBO9780511817434

Sun, L., & Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects [Themed Issue: Treatment Effect 1]. *Journal of Econometrics*, *225*(2), 175–199. https://doi.org/https://doi.org/10.1016/j.jeconom.2020.09.006

Torres, M. A. (2021). *Go green or go home? energy transition, directedtechnical change and wage inequality* (Doctoral dissertation).

Yamazaki, A. (2017). Jobs and climate policy: Evidence from british columbia's revenue-neutral carbon tax. *Journal of Environmental Economics and Management*, *83*, 197–216. https://doi.org/https://doi.org/10.1016/j.jeem.2017.03.003

Table 5: 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 6: 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 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)