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## Article

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# Green tax reforms with promotion of renewable energy sources and carbon capture and sequestration: Comparison of different alternatives

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## Abstract

The need to decarbonize economic production processes is undeniable and has been considered by most countries worldwide. Renewable Energy Sources (RES) and Carbon Capture and Sequestration (CCS) technologies appear among the most promising routes to the decarbonization process. We propose an equilibrium model where final-goods production uses labor and energy, and energy is generated using non-polluting RES and polluting fossil fuels. The government implements a Green Tax Reform (GTR), where it imposes a tax on emissions and uses revenues to finance subsidies to RES and support to CCS technologies. We test how results change according to the priority given to RES or to CCS support. Our results show that prioritizing RES support achieves better economic results and potentially also better environmental results. Overall, our empirical simulation demonstrates that resource substitution has a stronger benefit than decarbonizing fossil fuels.

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*Keywords:* Carbon capture and sequestration; Renewable energy sources; Environmental policy; Economy

## 1. Introduction

Decarbonization is a high priority worldwide, hence most countries have implemented measures to achieve cleaner and more sustainable production processes. Governments are committed to mitigation strategies, among which the promotion of Renewable Energy Sources (RES) and the development of Carbon Capture and Sequestration (CCS) technologies appear very promising. Both technologies still have relatively high costs and require policy intervention to become competitive [1]. Since governmental funds are limited, RES and CCS technologies compete for public support and funding. Most studies in the literature include both technologies as complements to reduce

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emissions, which they are, but do not look at the competition for public funding, and in that sense, they do not analyze which technology should be prioritized. RES development does not affect CCS growth and vice-versa, e.g., [2–8].

We contribute to the literature showing how different policy options impact the main variables under consideration and which technologies should be prioritized. We construct an equilibrium model, where final-good production uses energy and labor, and energy production uses RES and non-RES. A carbon tax is imposed on energy firms. Using a Green Tax Reform (GTR) logic, tax revenues are used to finance RES and CCS technologies. In the empirical analysis, we study how the main variables of our model evolve according to the revenue share devoted to RES support.

The paper is organized as follows, after this introduction, Section 2 provides a literature review, Section 3 describes the model, Section 4 presents the empirical implementation of the model, and Section 5 concludes the paper.

## 2. Related literature

Several articles include both CCS technologies and RES in Top-Down models. Typically, two approaches are followed. In the first group, the authors test the energy mixes that can meet up with specific climate/environmental goals or constraints. In this group we find, for example, [4,6,8]. In all cases the technologies' deployment was highly dependent on the environmental restrictions, but their growth was not very significant without policy support.

In the second group, which is in line with our study, authors test the macroeconomic and environmental effects of specific policy instruments, e.g., [2,3,5,7]. Once again, these studies showed the importance of policy instruments to promote the growth of RES as CCS shares.

Most articles do not use the GTR logic, i.e., carbon tax revenues are not used to finance subsidies or other technologies in a revenue neutral way. One exception is provided, e.g. [8].

## 3. The model

To simplify notation, capital letters indicate stocks, small letters indicate flows.

### 3.1. Model description

We consider a model in continuous time with four sectors: homogenous final-goods, energy generation, non-polluting renewable resources (R-sector) and polluting non-renewable resources or fossil fuels (F-sector). All production sectors act in perfect competition. We focus on the decentralized equilibrium. We ignore unnecessary aspects, e.g., we abstract from capital accumulation, savings and leisure decisions, in order to highlight key features, i.e., to isolate the effects of natural resources on the economy and the environment.

There is a mass  $[0,1]$  of identical individuals who consume final-goods and own firms, and there is no population growth such that all aggregate variables can be interpreted as per capita quantities.

Through the text the index  $t$  refers to the period.

#### *The environment*

In this economy, polluting emissions ( $p$ ) are a proportion,  $\psi$ , of fossil fuels ( $f$ ) use. The use of fossil fuels is measured in the units of the specific resource used while pollution is measured in tonnes of CO<sub>2</sub>. For simplicity, we abstract from leakage possibilities, and from carbon storage complications. The aggregate amount of pollution, in each moment, is  $p_t = (1 - \Omega_t)\psi f_t$  where  $\Omega_t$  is the share (%) of emissions abated at  $t$ .

#### *Government*

The government imposes a tax on emissions ( $\tau$ ) and allocates revenues to promote renewable resources ( $r$ ) through a subsidy ( $\sigma$ ), or to implement CCS activities. Both the tax and the subsidy are measured in monetary units, while renewables use is measured in units of the specific resource used. The government's budget is balanced at each time.

In the GTRs considered, the government invests both in RES and in CCS activities. To simplify, we assume that the CCS cost for tonne of CO<sub>2</sub>,  $c_{CCS}$  (measured in monetary units), is constant. The governmental budget is balanced at every moment:  $\tau_t(1 - \Omega_t)\psi f_t = \sigma_t r_t + c_{CCS}\Omega_t\psi f_t$ .

#### *Consumers*

Consumers have an instantaneous utility function,  $U(C_t, P_t)$ , which increases with consumption,  $C$ , which is a fraction of output ( $C_t = \lambda Y_t$ ), and decreases with pollution, i.e., individuals in this economy value a clean environment.

#### Final-goods sector

There are  $N$  ( $n = 1, \dots, N$ ) final-goods producers who face perfect competition. They produce ( $y$ ) using labor ( $l$ ) and energy ( $e$ ) according to  $y_t(l_t, e_t)$ .

#### Energy sector

There are  $Q$  ( $q = 1, \dots, Q$ ) energy producers facing perfect competition and producing energy using renewable ( $r$ ) and non-renewable ( $f$ ) resources,  $e_t(r_t, f_t)$ .

#### Renewable resources sector

In this sector there are  $Z$  ( $z = 1, \dots, Z$ ) firms which “extract” resources and sell them to energy generation firms. These firms can be interpreted as the owners of solar panels or wind turbines. For simplicity, they face a constant extraction cost,  $c_r$ . We do not consider scarcity or regeneration for  $r$  and, hence, we are not focusing on truly extractable resources such as biomass.

#### Non-renewable resources

In the  $F$  sector there are  $J$  firms ( $j = 1, \dots, J$ ) which extract resources and sell them to energy generation firms. As in the renewables sector, extraction costs,  $c_f$ , are constant. In reality, in the long term resource extraction costs would likely increase due to resources depletion, however, for simplicity we abstract from this issue. Each firm has an equal part of the total non-renewable resources stock and extracts accordingly  $f_{j,t}$ .

### 3.2. Implementation

Let us assume that the consumers’ utility function is given by  $U(C, P) = \ln C_t - \ln P_t$ . The aggregated final goods production function is  $y_t = A l_t^\alpha e_t^{1-\alpha}$ , where  $A$  represents the general efficiency of the economy,  $\alpha$  can be interpreted as the elasticity of output in relation to labor and  $(1 - \alpha)$  the elasticity of output in relation to energy. The aggregated production function in the energy sector is  $e_t = B r_t^\gamma f_t^{1-\gamma}$ , where  $B$  represents efficiency in this sector,  $\gamma$  can be interpreted as the elasticity of energy in relation to RES and  $(1 - \gamma)$  the elasticity of energy in relation to non-RES. Because non-RES consumption generates pollution, energy firms have to pay a carbon tax. In this way, the tax cost is internalized into the production sectors.

Final-good firms maximize profit ( $\pi_y = p_y y - w l - p_e e$ ) subject to the production function, where  $p_y$  is the final-good price which is normalized to one,  $w$  is the wage and  $p_e$  is the energy price. To simplify notation, we omit the time subscript in the following equations. The first order conditions (FOCs) give the demand functions for labor,  $l = \left(\frac{A\alpha}{w}\right)^{\frac{1}{1-\alpha}} e$ , and energy,  $e = \left(\frac{A(1-\alpha)}{p_e}\right)^{\frac{1}{\alpha}} l$  respectively.

These demand functions show, as expected, the degree of complementarity between the two production resources.

Energy generation firms maximize profit ( $\pi_e = p_e e - p_r r - p_f f - \tau p$ , where  $p_r$  and  $p_f$  are, respectively, the price paid for RES and non-RES) subject to the production function and the pollution function. The FOCs give the demand for RES,  $r = \left(\frac{p_e B \gamma}{p_r}\right)^{\frac{1}{1-\gamma}} f$ , and non-RES,  $f = \left(\frac{p_e B (1-\gamma)}{p_f + \tau(1-\Omega)\psi}\right)^{\frac{1}{\gamma}} r$ , respectively. As before, the demand functions show the degree of complementarity between the two types of resources.

In the RES sector, profit is given by  $\pi_r = p_r r - c_r r + \sigma r$ . The FOC in this sector gives the RES price,  $p_r = c_r - \sigma$ .

Hence, as expected the cost of using  $r$  increases with the extraction/production cost but decreases with the subsidy. In the non-RES, profit maximization in intertemporal (given the evolution of the reserves of fossil fuels). The instantaneous profit function is  $\pi_f = p_f f - c_f f$ . The FOC of the Current Value Hamiltonian, give, respectively, the  $f$  supply function,  $p_f = c_f + \lambda$ , and the law motion of the reserves shadow price ( $\lambda$ ),  $\dot{\lambda} = i$ . Where  $i$  is the interest rate. The cost of using  $f$  increases with extraction costs but there is no policy instrument affecting it, since the government follows the polluter pays principle.

Solving the model allows obtaining the expression for the energy price and for the wages:

$$p_e = \frac{1}{B} \left( \frac{c_f + \lambda + \tau(1-\Omega)\psi}{(1-\gamma)} \right)^{1-\gamma} \left( \frac{c_r - \sigma}{\gamma} \right)^\gamma \quad (1)$$

$$w = \frac{A^{\frac{1}{\alpha}} (1 - \alpha)^{\frac{1-\alpha}{\alpha}} \alpha B^{\frac{1-\alpha}{\alpha}} (1 - \gamma)^{\frac{1-\alpha}{\alpha}} \gamma^{\frac{1-\alpha}{\alpha}}}{(c_f + \lambda + \tau (1 - \Omega) \psi)^{\frac{(1-\gamma)(1-\alpha)}{\alpha}} (c_r - \sigma)^{\frac{\gamma(1-\alpha)}{\alpha}}} \quad (2)$$

Given the mathematical forms of our functions, we can also obtain the main expressions we are interested in. Energy per worker is given by:

$$\frac{e}{l} = \frac{A^{\frac{1}{\alpha}} (1 - \alpha)^{\frac{1}{\alpha}} B^{\frac{1}{\alpha}} \gamma^{\frac{\gamma}{\alpha}} (1 - \gamma)^{\frac{1-\gamma}{\alpha}}}{(c_f + \lambda + \tau (1 - \Omega) \psi)^{\frac{1-\gamma}{\alpha}} (c_r - \sigma)^{\frac{\gamma}{\alpha}}} \quad (3)$$

Output per worker, which represents the economy, is obtained dividing total output by the number of workers ( $\frac{y}{l} = A \left(\frac{e}{l}\right)^{1-\alpha}$ ):

$$\frac{y}{l} = A \left( \frac{A^{\frac{1}{\alpha}} (1 - \alpha)^{\frac{1}{\alpha}} B^{\frac{1}{\alpha}} \gamma^{\frac{\gamma}{\alpha}} (1 - \gamma)^{\frac{(1-\gamma)}{\alpha}}}{(c_f + \lambda + \tau (1 - \Omega) \psi)^{\frac{(1-\gamma)}{\alpha}} (c_r - \sigma)^{\frac{\gamma}{\alpha}}} \right)^{1-\alpha} \quad (4)$$

It is possible to see that the tax decreases output per worker, while abatement and the RES subsidy have a positive impact on it. This happens because the tax places an additional burden on the production side of the economy while the subsidy and abatement support alleviate that burden.

Together with energy per worker, the ratio of renewables over non-renewables represents the structure of the production:

$$\frac{r}{f} = \frac{(c_f + \lambda + \tau \psi (1 - \Omega)) \gamma}{(1 - \gamma) (c_r - \sigma)} \quad (5)$$

The carbon tax increases this ratio because it penalizes fossil fuel use which generate emissions. The subsidy to RES promotes resource substitution and therefore also has a positive impact on this ratio. Abatement negatively affects the ratio of renewables over non-renewables because it decarbonizes fossil fuels, hence in an economy that penalizes emissions it is extending the use of fossil fuels in time and postponing the resource substitution.

## 4. Empirical simulation

### 4.1. Implementation

To calibrate the initial extraction/production cost values, we focus on the electricity sector and consider the example of the United States of America (USA). For simplicity, we focus on only one RES and one non-RES for electricity generation, taking into account the productive structure of the generation sector. For the non-RES sector, we opt for coal since it is the most used and cheapest non-RES generation source. Additionally, it has a higher emission coefficient than gas, which means that CCS applied to coal plays a more important role in reducing CO<sub>2</sub> emissions. For RES, we exclude hydropower because it is already a mature source. We choose, instead, to focus on wind power. This renewable source has presented a significant growth in the last years and has become closely competitive with other sources. Our base year is 2010 (see Table 1).

**Table 1.** Calibration.

Parameter	Value	Sources
$c_r$	\$0.1012/kWh	[9]
$c_f$	\$0.07249/kWh	[9]
$\lambda$	\$0.01618/kWh	[10]
$\alpha$	0.67	[11]
$\gamma$	0.5	[12]
A,B	1	[12]
$\psi$	2.86	EIA
$c_{CCS}$	\$0.11/kWh	[13]

4.2. Empirical results

4.2.1. Base case

In this section we describe and compare the effects of the GTR as a function of the percentage of the tax that is dedicated to RES support. We characterize the general impacts on the economy. For the calculations we use the expressions  $\sigma r = x\tau(1 - \Omega)\psi f$  and  $\Omega_{CCS}\psi f = (1 - x)\tau(1 - \Omega)\psi f$ , where  $x$  indicates the percentage of the tax revenues allocated to RES support. Following IEA et al. (2010), we consider a tax of 30 USD per tonne of CO<sub>2</sub> that results in a value of 0.0264 USD/kWh for U.S. coal generation technologies.

We show how the policy instruments and the main variables of the economy behave as a function of  $x$  (Fig. 1).

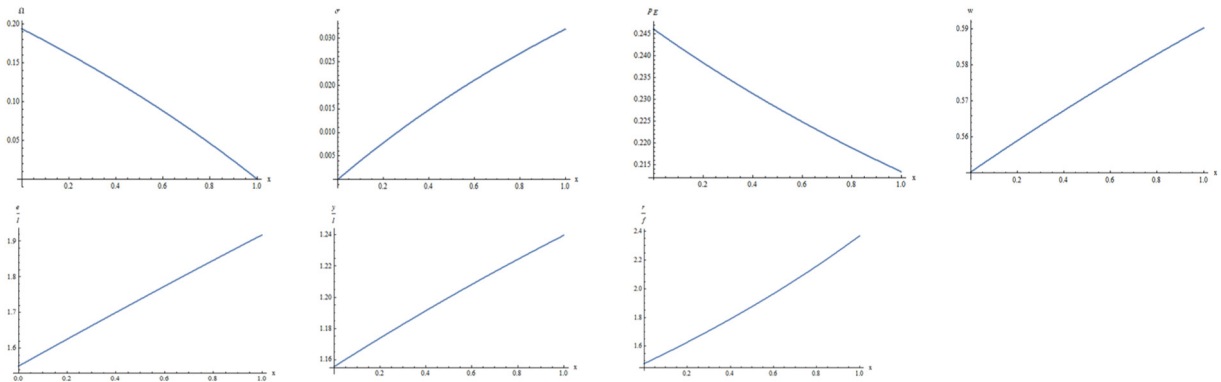


Fig. 1. Behavior of the policy instruments and the main variables as a function of the percentage dedicated to RES support.

With the increase of  $x$ , energy prices decrease which reflects the fact that resource substitution is cheaper than decarbonizing fossil fuels. With this effect there is an increase in output per worker and, consequently, wages increase due to higher productivity. Overall, these results indicate that the GTR has a positive economic effect and this effect is stronger through RES support than through CCS support.

The environmental effect can be assessed by energy use per worker combined with the ratio of RES over non-RES. The higher the share of tax revenues devoted to RES support, the higher the level of energy per worker due to lower energy prices. However, energy generation uses RES more intensively, i.e., the ratio of RES over non-RES increases, hence, the environmental outcome could also potentially be positive.

4.2.2. Sensitivity analysis

In this section we perform a sensitivity analysis to the tax level. We consider the intermediate value of 0.0264 USD/kWh as before and include a 50% lower tax (0.0132 USD/kWh) and a 50% higher tax (0.0396 USD/kWh). As can be seen in Fig. 2, a higher tax leads to a higher ratio of renewables over non-renewables, but to lower levels of output per worker and energy per worker.

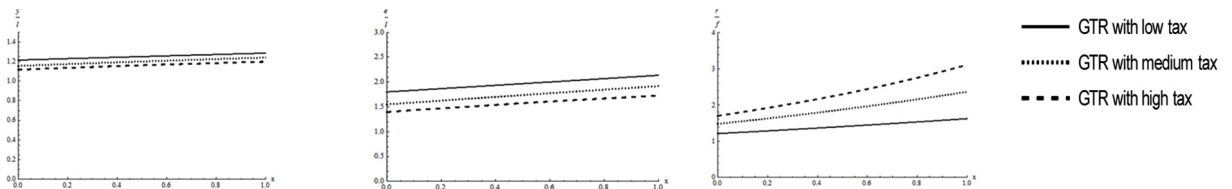


Fig. 2. Paths of the ratios  $\frac{y}{l}$ ,  $\frac{c}{l}$  and  $\frac{r}{l}$ .

5. Conclusions and policy implications

In this paper we contribute to the literature on decarbonization technologies. We assess Renewable Energy Sources (RES) and Carbon Capture and Sequestration (CCS) technologies and discuss which one should be

prioritized for public funding. We construct an equilibrium model, where final-goods production uses energy and labor, and energy generation uses RES and non-RES. A carbon tax is imposed on energy firms. Using a Green Tax Reform (GTR) logic, tax revenues are used to finance RES and CCS technologies. In the empirical analysis, we study how the main variables of our model evolve according to the revenue share devoted to RES support.

In our model, final-goods production uses labor and energy, and energy generation uses non-renewable (polluting) resources and renewable (non-polluting) resources. In the resources sectors extraction/production costs are constant.

We obtain the equilibrium of the model and test the behavior of the main variables when the share of the tax which is devoted to RES subsidies increases.

Our results indicate that the higher the priority given to RES support, the stronger the economic benefits of the GTR measured by output per worker. Energy prices are also lower, and wages are higher. Environmental effects are not as straightforward but can also be stronger with a higher priority given to RES since, even though energy per worker is higher, energy is generated using RES more intensively, i.e., there is a change in the production structure. Overall, our study indicates that when faced with financial constraints, policies should prioritize RES since resource substitution has stronger benefits than decarbonizing fossil fuels.

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