

Article

Energy Taxation Reform with an Environmental Focus in Portugal

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Abstract: Climate change has made the decarbonization of the different domestic economies a widely accepted and urgent priority. Yet, this is a very challenging task in a largely uncharted territory. In this context, in this paper, we address the issue of energy taxation reform with an environmental focus in Portugal. We do so using a multi-sector and multi-household dynamic computable general equilibrium model of the Portuguese economy. We analyze the environmental, macroeconomic, and distributional effects of different policies replacing current energy taxation with carbon taxation and, then, extend the carbon taxation to the levels necessary to achieve the IPCC 2018 emissions reduction targets. Our analysis indicates a clear path in the quest for decarbonization. First, replace energy taxes with a carbon tax; second, adopt the levels of carbon taxation necessary to achieve the emissions goals; third, use extra tax revenues from the carbon tax to reverse any potential adverse macroeconomic and distributional effects of carbon taxation. In the process, this would be a way around the pervasive problem of perverse fossil fuel subsidies, which would effectively disappear and, as such, would improve the efficiency of the tax system.

Keywords: energy taxes; perverse fossil fuel subsidies; CO₂ taxation; macroeconomic effects; distributional effects; dynamic computable general equilibrium; Portugal



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1. Introduction

Recently, a report of the Intergovernmental Panel on Climate Change [1] indicated that limiting global warming to 1.5 °C would require “rapid and far-reaching” transitions in land, energy, industry, buildings, transport, and cities. Global emissions of CO₂ would need to fall by about 45% from 2010 levels by 2030, reaching “net zero” around 2050, and neutrality of the remaining greenhouse gases would need to be achieved soon thereafter. In turn, the European Union legislative package “Clean Energy for All Europeans” [2] includes, among other measures, requirements for each Member State to draw up National Integrated Energy and Climate Plans, setting out the objectives, targets, and contributions of each Member State by 2030.

There is a wide gap between intentions and actions when it comes to environmental policies. This is mostly due to the difficulty in obtaining “fossil fuel prices right”, i.e., having fossil fuel prices also reflect the environmental externalities they generate (see, for example, [3–5]).

In the path toward obtaining “fossil fuel prices right”, there are two issues of critical importance. The first is the inadequacy of current energy taxation systems to do this job due to the focus on energy content and not emissions, and even more so the widespread existence of environmentally perverse fossil fuel subsidies that actually make fossil fuels even cheaper than the market mechanisms would dictate. (See, for example, [6–10]).

The second is the mechanisms to obtain “fossil fuel prices right” by environmental standards, in particular, through carbon taxation. (See, for example, [11–14]). In this context, there is strong evidence that carbon taxation without countervailing measures would lead to macroeconomic losses, loss of international competitiveness, and would

have adverse distributional effects. (See, for example, [15–19]). These adverse effects bring to the forefront the issue of recycling carbon tax revenues as a mechanism to mitigate such adverse effects while at the same time maintaining tax revenue neutrality, i.e., avoiding an increase in the overall tax burden for the domestic economy. [See, for example, [20–25]].

In Portugal, the main energy taxation exists under the so-called “*Imposto sobre Produtos Petrolíferos e Energéticos*”, ISP hereafter. This is a broad tax on petroleum and other energy products with tax revenues, which represents about 1.8% of the GDP. This tax has three main components: a basic unit tax, a road contribution component, and an add-on based on the carbon content of the products; more on which below. For the most part, the current energy tax system is designed mostly to reflect the energy content of fuels—rather than their emissions content—and is based on the need to raise funds for the public budget. In addition, it provides a large number of exemptions and subsidies on the use of different fossil fuels in transportation, agriculture, industrial processes, electricity generation, etc. In 2018, such exemptions and subsidies amounted to EUR 430 million or about 0.22% of the GDP or 12% of the ISP revenues. Accordingly, such environmentally perverse subsidies are substantial and pervasive.

In turn, in 2015, a carbon tax indexed to the carbon price in the EU-ETS was introduced as an add-on to the ISP tax. As such, this carbon tax has several serious shortcomings that make it a rather ineffective tool in desperate need of reform. In a nutshell, the existing carbon tax is hopelessly too low, it is far from universal, as it inherited all of the exemptions under energy taxation in Portugal, and contemplates no recycling mechanisms which would make it rather harmful to the economy and social justice should it be of a significant magnitude.

Faced with the IPCC 2018 targets and the EU 2019 directives, Portugal has recently approved the roadmap for carbon neutrality “*Roteiro para a Neutralidade Carbónica*” [26], RNC2050, hereafter. In the RNC2050, these different environmental and decarbonization targets are duly incorporated and specific decarbonization pathways are presented to achieve such targets. The RNC2050, however, is not intended to provide the specific public policy mechanisms necessary to get the country started in such pathways and to ultimately reach such targets. In this paper, we suggest a first strong step in the direction of decarbonization in the form of energy taxation reform.

The reality of energy and carbon taxation coupled with the need to achieve specific environmental goals fully justifies the need in Portugal for energy taxation reform. In this research, we focus on energy taxation reform with an environmental focus with the objective of getting fossil fuel prices right—allowing these prices to reflect the full costs of fossil fuel combustion activities. First, we analyze the effects of replacing the current tax on energy products with a carbon tax directly linked to the different environmental damages associated with fossil fuel combustion. Second, we extend the carbon taxation beyond what would be strictly necessary to replace the energy taxes, to the levels necessary to reach the international targets toward decarbonization. Third, we discuss a broader revenue-neutral fiscal reform that goes beyond the energy and carbon taxation margins, which would improve economic performance in the country while at the same time achieving the international targets toward decarbonization.

In these policy exercises, there are two important procedural aspects. First, we confine the analysis to the use of a tax on CO₂ emissions and not on overall emissions of greenhouse gases, GHG hereafter. Second, although we consider and report the effects of the different policies on the emissions of other GHG and air pollutants, these are not the focus of the current article. Our focus is exclusively on CO₂ emissions. This approach is consistent with the way carbon emissions are currently taxed in Portugal, as well as the terms of the current policy debate on the matter.

This paper uses a multi-sector, multi-household dynamic computable general equilibrium model of the Portuguese. Previous versions of this model are documented in [27,28] and were used to address several energy and climate policy issues (see [29–34]). The current version of the model has a detailed description of the tax system including energy

taxation. It features a fine differentiation of consumer and producer goods, particularly energy products. It captures the heterogeneity in income and consumption patterns by considering five differentiated household groups.

General equilibrium models have been used extensively in energy and environmental studies. Our approach follows the tradition of the early models developed in [35,36]. This means considering a highly disaggregated modeling of the economy in which the economic behavior of individual agents responds to prices and other market incentives and in which equilibrium outcomes are the result of their market interactions. In addition, such an approach considers a rather detailed specification of the tax system and government accounts. In its specifics, however, it is more directly linked to the contributions in, for example, [37–41]). In turn, thematically, this research is closer to [9,13,22,25]. This means a much greater detailed specification of the energy and environmental sectors, coupled with the consideration of individual and market intertemporal dynamics.

This paper is organized as follows. In Section 2, we present in very general terms the DGE model and discuss some implementation issues. In Section 3, we highlight some of the areas that were upgraded in this version of the model with direct relevance for this research. Section 4 presents the simulation results for a simple replacement of the ISP with a CO₂ tax. Section 5 does the same but includes the extra CO₂ taxation necessary to achieve IPCC goals. Finally, Section 6 offers a summary of the results, policy recommendations, and some thoughts about future research.

2. The Dynamic Computable General Equilibrium Model

What follows is a very brief description of the general features and implementation of the dynamic computable general equilibrium model of the Portuguese economy, DGE hereafter (see [25] for further details). In addition, and in order to provide a better understanding of the main features of the model, we provide some basic information about the model structure and parametrization of an aggregate version of the model in Appendix A.

2.1. The General Features

The dynamic multi-sector general equilibrium model of the Portuguese economy incorporates fully dynamic optimization behavior, detailed household accounts, detailed industry accounts, a comprehensive modeling of the public sector activities, and an elaborate description of the energy sectors. We consider a decentralized economy. There are four types of agents in the economy: households, firms, the public sector, and the foreign sector. All agents face financial constraints that frame their choices. All agents are price takers and have perfect foresight. See Figure 1 for a depiction of the general structure of the model and Figure 2 for the structure of its energy module.

Households and firms implement optimal choices, as appropriate, to maximize their objective functions. Households maximize their intertemporal utilities subject to an equation of motion for financial wealth, thereby generating optimal consumption, labor supply, and savings behaviors. We consider five household income groups per quintile. While the general structure of household behavior is the same for all household groups, preferences, income, wealth, and taxes are household-specific, as are consumption demands, savings, and labor supply. [See [41] for an alternative multi-criteria approach.]

Firms maximize the net present value of their cash flow, subject to the equation of motion for capital stock to yield optimal output, labor demand, and investment demand. We consider twenty-four production sectors covering the whole spectrum of economic activity in the country. These include energy-producing sectors, such as electricity and petroleum refining, other EU-ETS sectors, such as transportation, textiles, wood pulp and paper, chemicals and pharmaceuticals, rubber, plastic and ceramics, and primary metals, as well as sectors not in the EU-ETS, such as agriculture, basic manufacturing, and construction. While the general structure of production behavior is the same for all sectors, technologies, capital endowments, and taxes are sector-specific, as are output supply, labor demand, energy demand, and investment demand. The public sector and the foreign sector

evolve in a way that is determined by the economic conditions and their respective financial constraints.

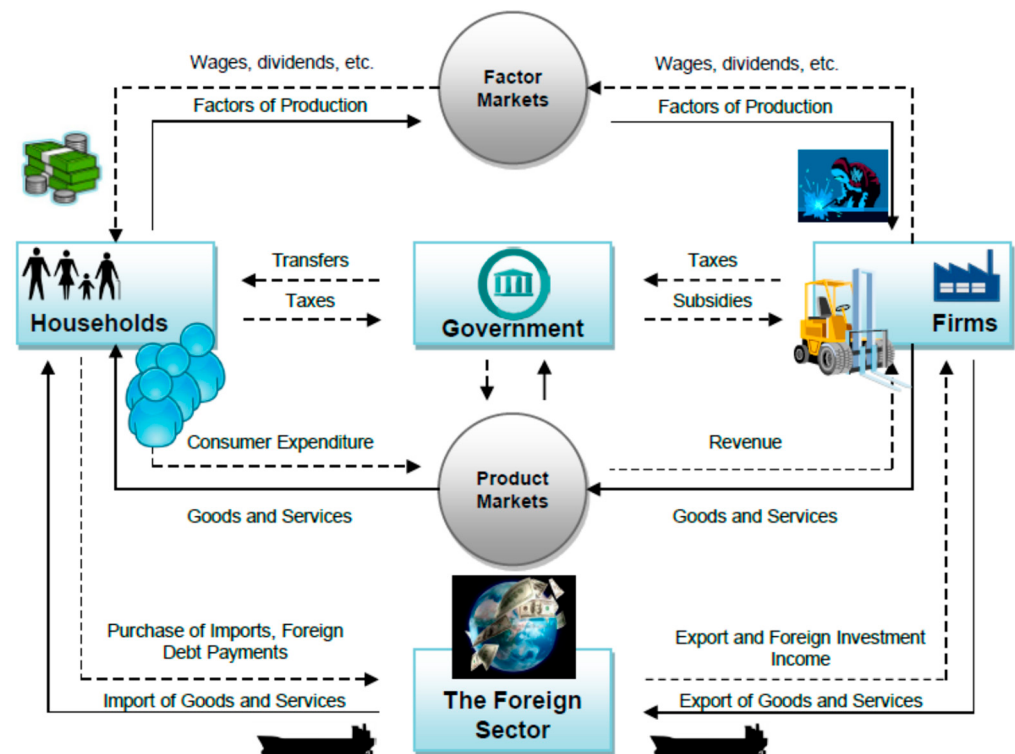


Figure 1. The DGE Model.

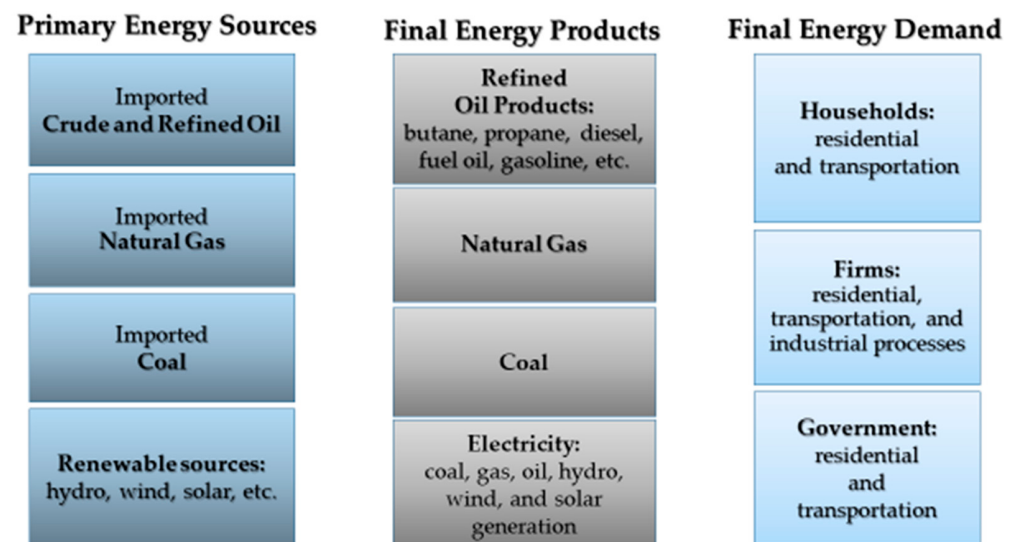


Figure 2. The Energy Module.

All economic agents interact in different markets. The general market equilibrium is defined by market clearing in product markets, labor markets, financial markets, and the market for investment goods. The equilibrium of the product market reflects the national income accounting identity and the different expenditure allocations of the output by sector of economic activity. The total amount of a commodity supplied to the economy, be it produced domestically, or imported from abroad, must equal the total end-user demand for the product, including the demand by households, by the public sector, its use as an intermediate demand, and its application as an investment good. See Figure 1 for a stylized presentation of the model.

The total labor supplied by the different households, adjusted by an exogenous and constant unemployment rate, is endogenously determined. It must equal the total labor demanded by the different sectors of economic activity. There is only one equilibrium wage rate, although this translates into different household-specific effective wage rates, based on household-specific levels of human capital which obviously differ by quartile of income. Different firms buy shares of the same aggregate labor supply. Implicitly, this means that we do not consider differences in the composition of labor demand among the different sectors of economic activity, in terms of the incorporated human capital levels. Saving by households and the foreign sector equals the value of domestic investment plus the budget deficit.

The evolution of the economy is described by the optimal change in the stock variables—household-specific financial wealth and sector-specific private capital stock, as well as their respective shadow prices. The evolution of the stocks of public debt and foreign debt act as resource constraints in the overall economy. The endogenous and optimal changes in these stock variables—investment, saving, budget deficit, and current account deficit—provide the link between subsequent periods. The model can be conceptualized as a large set of nonlinear difference equations, where flow variables are determined through optimal control rules.

The intertemporal path for the economy is described by the behavioral equations, the equations of motion for the stock and shadow price variables, and the market equilibrium conditions. We define the steady-state growth path as an intertemporal equilibrium trajectory in which all the flow and stock variables grow at the same rate while market and shadow prices are constant.

2.2. Calibration

The model is calibrated with data for the period 2005–2014 and stock values for 2015. The calibration of the model is designed to allow the model to replicate as its most fundamental base case, a stylized steady state of the economy, as defined by the trends and information contained in the data set. In the absence of any policy changes, or any other exogenous changes, the model's implementation will just replicate into the future such stylized economic trends. Counterfactual simulations thus allow us to identify the marginal effects of any policy or exogenous change as deviations from the base case. The use of data for a long period in the calibration process, specifically a ten-year window covering a full business cycle, allows us to capture the long-term economic trends for the economy without undue contamination by business cycle effects. The period under consideration represents the most recent period for which at the time of the model development it was possible to gather comprehensive and consistent data and parameter calibration sets, due to the high demands of the model.

The existence of a steady state imposes three types of calibration restrictions. First, it determines the value of critical production parameters, such as adjustment costs and depreciation rates, given the initial capital stocks. These stocks, in turn, are determined by assuming that the observed levels of investment are such that the ratios of capital to GDP do not change in the steady state. Second, the need for constant public debt and foreign debt to GDP ratios implies that the steady-state budget deficit and the current account deficit are a fraction of the respective stocks of debt equal to the steady-state growth rate. Finally, the exogenous variables, such as public or international transfers, have to grow at the steady-state growth rate. As an indication, for calibration purposes, the steady-state growth rate considered, i.e., the average GDP growth rate for the calibration period was 0.1%.

2.3. Numerical Implementation

The dynamic general equilibrium model is fully described by the behavioral equations and accounting definitions, and thus constitutes a system of nonlinear equations and nonlinear first-order difference equations. No objective function is explicitly specified,

on account that each of the individual problems (the household, firm, and public sector) are set as first order and Hamiltonian conditions. These are implemented and solved using the GAMS (general algebraic modeling system) software and the MINOS nonlinear programming solver.

MINOS uses a reduced gradient algorithm generalized by means of a projected Lagrangian approach to solve mathematical programs with nonlinear constraints. The projected Lagrangian approach employs linear approximations for the nonlinear constraints and adds a Lagrangian and penalty term to the objective to compensate for approximation error. This series of sub-problems is then solved using a quasi-Newton algorithm to select a search direction and step length.

2.4. The Reference Scenario and the Identification of the Effects of Policies

The reference scenario provides a trajectory for the economy through 2050. The reference scenario embodies several assumptions regarding climate policy, which are superimposed on the steady-state trajectory used in the calibration of the model. The main assumptions in our reference scenario are as follows. First, we assume that the current levels of carbon taxation persist through 2050. Second, we recognize that the major coal-fired power plants ceased operations at the end of their life span, and no additional coal generation capacity is scheduled for installation. As such, coal is exclusively used outside the electricity generation sector. Third, we assume that fossil fuel prices follow forecasts given by the International Energy Agency [42]. Although fossil fuel price forecasts are notoriously imprecise and volatile, the effects of assuming different price scenarios would not change the main message of the paper, although it would necessarily change some of the actual figures presented.

The effects of the different policy experiments are obtained by comparing the results of the counterfactual simulations against the results under the reference scenario. Specifically, for any given year, effects are presented as percentage deviations of the counterfactual results from the base case results for the same year. Accordingly, say for 2030, the effects of a given policy are measured as the deviation of the outcome of such policy in 2030 from the base case outcome in 2030. This provides a measure of the effects of policies that is independent of the actual reference scenario.

Now, by their very nature general equilibrium results are generated simultaneously considering all possible interactions and feedback among the different variables in the model. For the sake of clarity of presentation, however, we present the effects of the different policies in a sequential manner. We start by considering the effects of the different policies on energy prices. This is the point of the initial impact of the different policies. Then, we consider the effects on the different energy markets. We consider changes in the levels and composition of energy demand and energy generation. Ultimately, this also allows us to measure the environmental impacts of the policies. Then, we consider how the changes in energy prices affect the economy both at the macroeconomic level and at the industry levels. Finally, we consider the effects on households and, specifically, the welfare effects of the policies on different income groups.

3. Some Extensions to the DGEP Model

In this section, we provide more detailed information about some of the new features of the DGEP model, which are directly relevant to this research.

3.1. A Detailed Disaggregation of Production Sectors and Energy Inputs

We consider 24 sectors of economic activity encompassing all areas of economic activity. See Table 1 for the list of sectors as well as for some basic descriptive statistics.

This disaggregation allows us to identify the sectors of economic activity that produce goods that are internationally traded and those that do not. The sectors engaged in significant international trade include petroleum refining, food, textiles, wood, chemicals, rubber, basic metals, equipment, and transportation. These sectors account for 90% of

exports. Yet, they represent just 28.5% of total output and 17.9% of total employment. Equally important, they are very high energy-intensive sectors, which are responsible for 45.7% of total energy expenditures.

Table 1. Sectors of economic activity: definition and basic information.

	Output	Employment	Exports	Energy	CO ₂ Emissions
Total	100.0	100.0	100.0	100.0	100.0
Petroleum refining	3.9	0.0	5.3	24.4	8.6
Electricity	4.2	0.2	0.2	28.9	35.5
Biomass	0.3	0.0	-	0.0	
Agriculture	3.6	10.2	1.8	1.8	2.7
Mining	0.9	0.2	1.1	0.7	0.9
Food products, beverages, and tobacco	5.6	2.2	7.8	2.0	2.2
Textiles	2.8	4.3	11.3	1.3	2.3
Wood, and pulp and paper	2.1	1.2	6.6	1.4	2.2
Chemicals and pharmaceuticals	2.6	0.4	6.2	2.2	2.1
Rubber, plastics, and ceramics	2.1	1.3	7.5	2.6	16.3
Basic metals and fabricated metal products	2.1	1.8	8.2	1.0	1.1
Equipment manufacturing	4.2	3.3	27.3	0.6	0.7
Water, sewage, and waste management	1.2	0.8	0.7	0.7	1.0
Construction	6.9	5.8	1.1	1.6	4.1
Wholesale and retail trade	10.6	15.5	0.2	10.2	5.0
Transportation	4.8	3.4	9.7	9.9	9.6
Accommodation and food services	4.0	6.1	1.1	1.7	1.1
Information technology	3.6	1.8	2.2	0.5	0.1
Finance and insurance	4.8	1.8	1.1	0.5	0.2
Real estate	7.2	1.0	-	0.4	0.1
Professional services	6.6	13.0	0.7	1.4	1.0
Public administration	5.3	5.9	-	2.6	1.4
Education	3.7	6.9	-	0.7	0.3
Health	4.7	8.7	-	1.9	1.3

In turn, we consider eleven types of energy inputs: crude oil; coal; natural gas; butane; propane; LPG; fuel oil; gasoline; diesel; electricity; and biomass.

3.2. A Detailed Specification of the Energy Taxation

The tax on petroleum products raised EUR 3.086 billion in 2015, approximately 1.8% of GDP and 5% of total public sector receipts, including tax revenues and social contributions.

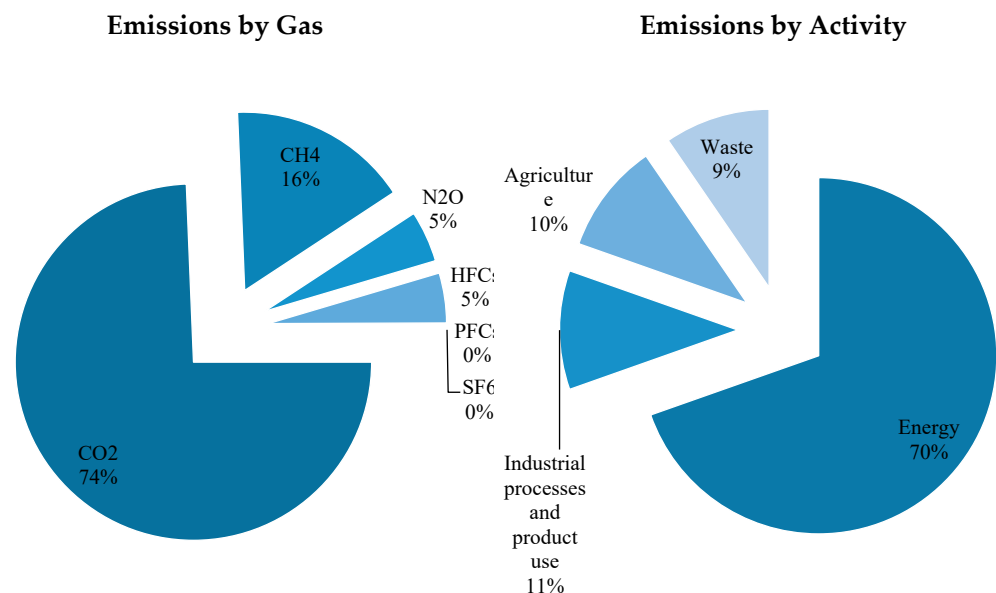
The final sale price of energy products includes the following components: the base price per physical unit; the tax on petroleum products; and an additional value tax that is levied as a fraction of the base price plus the unit tax. Specifically, the tax on petroleum products, the ISP, includes a basic unit tax; the contribution for road service design to finance maintenance of the national road network; and an add-on tax on emissions of CO₂. Table 2 includes details about these three components for a whole variety of fuels.

3.3. A Detailed Specification of GHG Emissions and other Air Pollutants

We incorporate in the model GHG emissions considered within the common reporting framework of the IPCC framework (see, for example, [1]), which represent the whole universe of GHG pollutants in Portugal: carbon dioxide (CO₂); methane (CH₄); nitrous oxide (N₂O); hydrofluorocarbons (HFC); [perfluorocarbons (PFC); and sulfur hexafluoride (SF₆) (See Figure 3).

Table 2. The ISP and its components.

	Units	Total Tax Rate (Euro per Unit)	Unit Tax	Road Contribution (Euro per Unit)	CO ₂ Add-On
Butane/Propane	kg	0.02480	0.00799		0.01681
Electricity	MWh	1.00000	1.00000		
Fuel Oil	kg	0.03686	0.01565		0.02121
Natural Gas	GJ	0.68429	0.30000		0.38429
Natural Gas (vehicular)	GJ	3.22429	2.84000		0.38429
Diesel (Colored and Marked)	l	0.09446	0.07751		0.01695
Diesel Heating Oil	l	0.34695	0.33000		0.01695
Diesel	l	0.40636	0.27841	0.11100	0.01695
Gasoline	l	0.62151	0.51895	0.08700	0.01556
LPG Auto	l	0.27076	0.12788	0.12300	0.01988

**Figure 3.** Greenhouse gas emissions.

Of the GHG considered, carbon dioxide, and in a small part methane, are directly related to the combustion of fossil fuels. In turn, the bulk of emissions from methane and remaining GHG derive mostly from agriculture and a variety of industrial processes.

In turn, we incorporate in the model the air pollutants considered within the National Emission Ceiling Directive of the European Energy Agency [43]: nitrogen oxide (NO_x); sulfur dioxide (SO₂); particulate matter (PM) 10 µm in diameter and 2.5 µm in diameter; volatile organic compounds (VOCs); carbon monoxide (CO); and ammonia (NH₃) (See Figure 4).

These air pollutants are induced by the combustion of fossil fuels, either directly as is the case of nitrogen oxide and sulfur dioxide, or indirectly by road transportation activities such as particulate matter, volatile organic matter, and carbon monoxide. These are the relevant co-pollutants when we consider policies designed to reduce carbon dioxide emissions.

We model emissions of the different GHG and air pollutants in two different ways. For emissions that are generated by fossil fuel combustion, i.e., the co-pollutants with carbon dioxide, we model emissions as a direct function of the amount of the fossil fuel used in the corresponding activities. For emissions that are induced by agriculture and

industrial processes, we modeled them as a fixed function of the output of each of the different production sectors or activities.

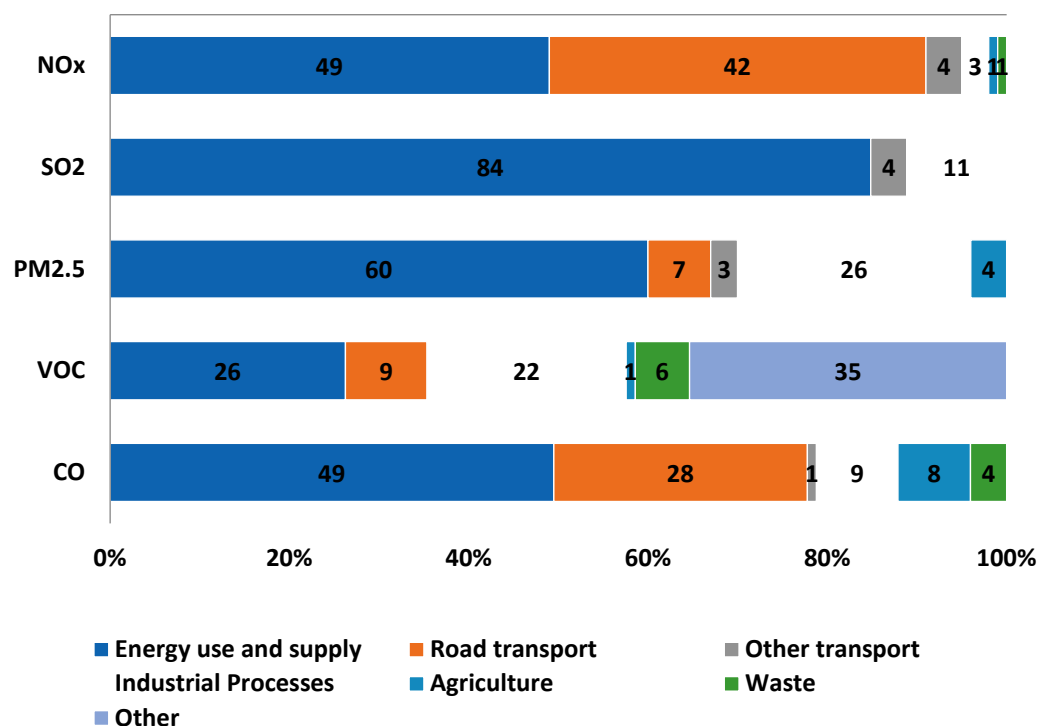


Figure 4. Air pollutant emissions.

From a conceptual perspective, for fossil fuel-based emissions, carbon dioxide, and its co-pollutants, we capture the following three effects: effects due to fossil fuel switching; effects due to changes in the level of economic activity; and effects due to changes in the composition of economic activity. For process-based emissions, we capture only the last two effects.

4. Energy Taxation Reform with an Environmental Focus

To establish the effects of replacing the ISP with an equivalent CO₂ tax we start by analyzing the effects, in isolation, of a CO₂ tax of the magnitude necessary to replace the current ISP energy taxation. In this case, the CO₂ tax is levied in addition to the current ISP taxation. We refer to this scenario henceforth as CF1. Then, we compare this scenario with a revenue-neutral experiment, in which the CO₂ tax replaces the ISP taxation. We refer to this scenario as CF2. We present summary simulation results in Tables 3–8.

4.1. On the Effects of a CO₂ Tax under the Current Energy Taxation Framework

The CF1 scenario corresponds to the implementation of a CO₂ tax of the magnitude necessary to replace the ISP, without actually replacing the ISP. The magnitude of the carbon tax necessary for this purpose is endogenously determined. Simulation results determined that the magnitude of the carbon tax is EUR 114 per ton of CO₂, yielding additional tax revenues that are approximately 1.85% of the GDP.

4.1.1. Effects on the Energy Markets and Emissions

The introduction of this CO₂ tax leads to an increase in energy prices of 13.91%, which leads to a decrease in energy demand by 12.40%. The price of domestic electricity generation increases by 12.59%, which leads to a 10.17% decrease in domestic production and a 12.81% increase in imports. Overall electricity demand declines by 9.80%. Accordingly, the share of electricity in final energy demand increases by 2.97%.

Table 3. Long run [2030] effects: energy markets.

	CF1	CF2	CF3	CF4	CF4A	CF4B
Carbon Tax	114	114	120–190	120–190	120–190	120–190
Energy Price	13.91	0.55	8.52	3.72	9.03	3.47
Electricity Price	12.59	7.31	12.66	3.65	13.59	3.30
Electricity Production	−10.17	−5.37	−9.54	−1.75	−7.65	−2.71
Thermal Generation	−25.61	−20.18	−29.31	−25.52	−27.83	−26.28
Renewable Energy Systems	−2.18	7.83	5.89	9.50	7.85	8.48
Net Electricity Imports	12.81	9.20	14.15	6.06	18.26	4.33
Energy Demand	−12.40	−4.36	−10.58	−4.47	−8.62	−5.36
Electricity Demand	−9.80	−5.13	−9.16	−1.62	−7.23	−2.59
% Electricity in Final Demand	2.97	−0.80	1.59	2.99	1.52	2.92

Percentage change from the corresponding year in the reference case.

Table 4. Long run [2030] effects: greenhouse gas and air pollutant emissions.

	CF1	CF2	CF3	CF4	CF4A	CF4B
Greenhouse Gas Emissions						
CO₂ Emissions Relative to 2010	53.8%	60.2%	52.7%	55.1%	53.6%	54.2%
Carbon Dioxide—CO₂	−36.02	−28.26	−37.64	−34.76	−36.16	−35.34
Methane—CH₄	−25.29	−16.57	−26.75	−23.39	−25.01	−24.04
Nitrous Oxide—N₂O	−30.73	−22.39	−32.16	−29.03	−30.56	−29.66
Hydrofluorocarbons—HFC	−5.66	−0.94	−4.07	2.56	−3.80	3.56
Perfluorocarbons—PFC	−4.96	−0.96	−3.69	2.02	−3.31	2.60
Sulfur Hexafluoride—SF₆	−10.17	−5.37	−9.54	−1.75	−7.65	−2.71
Air Pollutant Emissions						
Nitrogen Oxide—NO_x	−37.22	−29.01	−37.90	−34.97	−36.44	−35.57
Sulfur Dioxide—SO₂	−43.13	−35.66	−44.14	−41.45	−42.82	−42.01
Volatile Org. Compounds—VOC	−23.67	−15.36	−26.37	−23.18	−24.65	−23.81
Carbon Monoxide—CO	−51.08	−45.62	−54.54	−52.74	−53.39	−53.20
Particulate Matter—PM	−71.71	−69.19	−77.22	−76.57	−76.59	−76.85
Ammonia—NH₃	−11.93	−1.44	−3.98	0.35	−3.17	0.37

Percentage change from the corresponding year in the reference case.

Table 5. Long run [2030] effects: macroeconomic performance.

	CF1	CF2	CF3	CF4	CF4A	CF4B
GDP	−5.21	−1.19	−3.97	1.46	−3.06	1.72
Private Consumption	−1.21	−0.12	−0.78	1.18	2.34	−0.85
Investment	−1.33	0.02	−0.61	1.63	0.37	1.63
Employment	−2.71	−0.56	−2.03	0.90	−1.00	0.88
Foreign Debt	−12.66	0.64	−1.53	−3.59	−3.38	−0.79
Public Debt	3.70	2.26	3.59	−0.90	7.20	−2.98
CPI	2.32	0.38	1.65	0.53	2.49	0.03

Percentage change from the corresponding year in the reference case.

Table 6. Long run [2030] effects: energy taxes.

	Reference	CF1	CF2	CF3	CF4	CF4A	CF4A
Unit Tax	2.28	3.90	2.30	3.22	3.37	3.30	3.34
CSR	0.22	0.21	0.23	0.22	0.22	0.22	0.22
ISP	1.90	1.84	0.00	0.00	0.00	0.00	0.00
CO₂	0.16	1.85	2.07	3.01	3.15	3.08	3.12

Percent of GDP.

Table 7. Long run [2030] effects: output by industry.

	CF1	CF2	CF3	CF4	CF4A	CF4B
Total	−5.21	−1.19	−1.53	−3.59	−3.38	−0.79
Petroleum refining	−11.16	0.64	−0.18	−0.21	−0.18	−0.07
Electricity	−10.17	−5.37	1.43	1.57	1.48	0.62
Biomass	2.04	2.29	−1.34	−3.63	−11.05	2.57
Agriculture	−4.39	−1.50	−1.40	−20.39	1.66	−44.25
Mining	−9.07	−0.96	−2.02	0.90	−1.01	0.88
Manufacture of food products, etc.	−3.05	−0.28	0.59	1.53	4.60	−1.00
Textiles	−8.13	−5.04	40.21	46.50	43.65	45.05
Wood, and pulp and paper	−7.81	−4.66	−1.53	−3.59	−3.38	−0.79
Chemicals and pharmaceuticals	−8.12	−2.67	−0.18	−0.21	−0.18	−0.07
Rubber, plastics, and ceramics	−13.49	−9.09	1.43	1.57	1.48	0.62
Basic metals and metal products	−10.35	−4.12	−1.34	−3.63	−11.05	2.57
Equipment manufacturing	−16.91	−1.62	−1.40	−20.39	1.66	−44.25
Water, sewage, and waste management	−2.02	−0.71	−2.02	0.90	−1.01	0.88
Construction	−1.80	−0.21	0.59	1.53	4.60	−1.00
Wholesale and retail trade	−5.86	−0.25	40.21	46.50	43.65	45.05
Transportation	−9.50	0.75	−1.53	−3.59	−3.38	−0.79
Accommodation and food services	−2.37	−0.41	−0.18	−0.21	−0.18	−0.07
Information technology	−1.95	−0.42	1.43	1.57	1.48	0.62
Finance and insurance	−2.61	−0.45	−1.34	−3.63	−11.05	2.57
Real estate	−0.82	−0.12	−1.40	−20.39	1.66	−44.25
Professional services	−3.48	−0.57	−2.02	0.90	−1.01	0.88
Public administration	−0.94	−0.42	0.59	1.53	4.60	−1.00
Education	−0.58	−0.18	40.21	46.50	43.65	45.05
Health	−1.32	−0.37	−1.53	−3.59	−3.38	−0.79
Other	−2.68	−0.43	−0.18	−0.21	−0.18	−0.07

Percentage change from the corresponding year in the reference case.

Table 8. Long run [2030] effects: welfare effects.

	CF1	CF2	CF3	CF4	CF4A	CF4B
Equivalent Variation in Income						
All Households	−1.34	−0.10	−0.86	1.09	2.26	−0.94
First Quintile (lowest income)	−1.85	−0.22	−1.25	2.51	4.84	−1.08
Second Quintile	−1.64	−0.12	−1.04	1.71	3.35	−0.99
Third Quintile	−1.45	−0.09	−0.92	1.25	2.56	−0.96
Fourth Quintile	−1.33	−0.09	−0.85	0.85	1.82	−0.94
Fifth Quintile (highest income)	−1.02	−0.08	−0.65	0.53	1.24	−0.86

Percentage change from the corresponding year in the reference case.

The introduction of this CO₂ tax leads to a reduction in CO₂ emissions of 36.02%, which represents 53.8% of the 2010 levels. Significant reductions are also induced in other GHG emissions, in particular, CH₄ and N₂O emissions, with smaller reductions in emissions observed for HP, PF, and SF₆. In turn, the emissions of air pollutants are reduced greatly as well. This is true, particularly, for NO_x, SO₂, and VOC emissions, and less so for CO and PM emissions.

4.1.2. Macroeconomic and Distributional Effects

The macroeconomic effects of the CO₂ tax are naturally adverse. GDP declines by 5.21% linked directly on the supply side to the reduction in investment by 1.33% and employment by 2.71%, and on the demand side by a reduction in private consumption of 1.21%. The consumer price index, CPI hereafter, increases by 2.32%. In turn, foreign debt increases by 3.70%, with greater reliance on relatively cheaper foreign goods. Finally, there is, by construction, a reduction of 12.66% in public debt.

The industries that are the most adversely affected in terms of their output are petroleum refining and electricity generation, as expected, as well as rubber, plastic and ceramics, basic metals, equipment, and transportation, as well as textiles, wood, and chemicals. These are all energy-intensive sectors that produce internationally traded goods.

Overall, there is an aggregate household welfare loss of 1.34%. Across the different household income groups, this loss is felt in a regressive manner. Indeed, the lowest income group suffers a loss of 1.85% while the highest income group loses just 1.02%. Accordingly, the factor of regressivity is 1.8.

4.2. On the Effects of Replacing the ISP with a CO₂ Tax

In a CF2 simulation, we use the proceeds of the EUR 114 per ton of CO₂ tax discussed above to replace the ISP in a revenue-neutral manner. Effectively, this experiment consists in transforming the ISP from a tax based on the energy content of the different fuels into an environmental tax based on CO₂ emissions content.

4.2.1. Effects on Energy Markets and Emissions

Energy prices increase marginally by 0.55% and energy demand declines by just 4.36%. The price of electricity generation increases by 7.31%, which leads to a reduction of 5.37% in production. The production from renewables increases by 7.83%, while imports increase by 9.20%. Overall, the share of electricity in final energy demand declines by 0.80%. Compared to CF1, all results under CF2 are smaller. The most important differences in CF2 are the increase in electricity production from renewable sources and the relative decline in the share of electricity in final demand.

Under CF2, CO₂ emissions declined by 28.26%. This means that emissions by 2030 represent 60.2% of emissions in 2010. The remaining emissions of both GHG and air pollution are also less pronounced but maintain the patterns observed before. The lower reductions compared to CF1 are due to the replacement of the energy taxes as opposed to the mere addition of a CO₂ tax.

4.2.2. Macroeconomic and Distributional Effects

The substitution of the energy taxes with a CO₂ tax leads to a decline in GDP of 1.19% with private investment remaining essentially unchanged and employment declining by just 0.56%. The CPI shows a small increase of 0.38% and for private consumption, a marginal decline of 0.12%. Foreign debt increases but just by 2.26% while, naturally, the public debt by definition is just marginally affected. Overall, compared to CF1, we observe smaller adverse macroeconomic effects.

The reduction in economic activity observed at the aggregate level hides some interesting industry effects. While electricity generation declines, the production of the refining sector increases, albeit only marginally. This reflects the switch in the focus of taxation of the sector but not a meaningful net increase in the tax burden on the sector. Along the same lines, transportation services also show increased production. The remaining industries that are adversely affected are the same as under CF1 but with greatly reduced effects under CF2, in particular the cases of chemicals, basic metals, and equipment.

The adverse household welfare effects are now much smaller, a loss of just 0.10%. Yet, the same patterns of regressivity can be observed, as the lowest household income group sees a loss of 0.22% and the highest income group of less than 0.08%. The factor of regressivity is 2.7.

5. On the Effects of Energy Taxation Reform while Reaching IPCC Targets

Having reached this point, it is clear that there are benefits to energy taxation reform. It is also clear that there are adverse efficiency and distributional effects. More fundamentally, this reform does not generate the reductions in CO₂ emissions necessary to reach the IPCC 2018 targets.

In this new set of experiments, we consider the effects of energy tax reform while at the same time increasing CO₂ taxation to the levels necessary to reach IPCC emissions targets. The new levels of CO₂ taxation are, naturally, much larger than what would be strictly necessary to replace the ISP. In terms of the experiments considered, we look first to a case in which the revenues from the CO₂ taxation in excess of what is necessary to finance the energy taxation reform reverts to the general public budget, i.e., a non-recycling case. We refer to this scenario henceforth as CF3. Second, we consider the recycling of these extra CO₂ revenues in ways conducive to improving the economic and distributional outcomes. We refer to this scenario henceforth as CF4. We present the simulation results in Tables 3–8, as before.

5.1. Effects of Energy Taxation Reform without Revenue Recycling

To reach a reduction in CO₂ emissions by 2030 of 45% relative to 2010 levels, we need a CO₂ tax rate that increases from EUR 114 to 190 per ton of CO₂. As before, these levels are endogenously determined in the model simulations. We consider an increasing level of taxation reflecting the increasing marginal costs of emissions abating.

5.1.1. Effects on Energy Markets and Emissions

Under CF3, energy prices increase by 8.52% and energy demand decreases by 10.58%. The price of electricity generation increases by 12.66%, which leads to a 9.54% reduction in production. Production of electricity from renewable energy resources increases by 5.89% while imports increase by 14.15%. Overall, the share of electricity in final energy demand increases by 1.59%.

Compared to CF2, results in CF3 are of a much greater magnitude, in some cases almost doubling the effect, which suggests rapidly increasing marginal abatement costs. Qualitatively, the most important difference is the increase in the relative role of electricity in final energy demand directly induced by a change in the relative prices of electricity to fossil fuels.

Under CF3, CO₂ emissions decrease by 37.64%. As such, emissions by 2030 will represent 52.7% of emissions in 2010, which marginally exceeds what is required under the IPCC target. GHG and air pollution emissions are much reduced compared to CF2 due to higher levels of CO₂ taxation.

Reductions in emissions across the board are similar to the ones observed under CF1—a case in which a CO₂ tax of EUR 114 per ton is imposed on top of the existing energy tax system. This suggests that from an environmental perspective, a carbon tax of EUR 114 per ton of CO₂ added to the status quo has the same environmental effects as a tax starting at EUR 114 and increases to EUR 190 by 2030, which includes the replacement of current energy taxes.

5.1.2. Macroeconomic and Distributional Effects

Under CF3, there is a decrease in GDP of 3.97%, with private investment decreasing by 0.61% and employment decreasing by 2.03%. The CPI increases by 1.65% and private consumption decreases by 0.78%. Foreign debt increases by 3.59% while public debt decreases by 1.53% due to the added CO₂ tax revenues and despite a decreasing tax base.

Overall, compared to CF2, we observe significantly larger negative macroeconomic effects. This reinforces the evidence supporting sharply increasing marginal abatement costs for CO₂ emissions. More importantly, compared to CF1—a case with similar environmental effects—the adverse macroeconomic effects are now clearly smaller, although still sizeable.

Under CF3, the industries most affected include electricity production, petroleum refining, agriculture, mining, textiles, wood, chemicals, rubber, basic metals, equipment, trade, and transportation. These are essentially the same industries that are most affected under CF2, although the adverse effects are now larger. In particular, the adverse effects on petroleum refining, trade, and transportation are significantly larger. In turn, compared to

CF1, all of these adverse effects are smaller, in particular for sectors such as refining and transportation, sectors that are directly affected by the current energy taxation.

The adverse household welfare effects under CF3 are a loss of 0.86%. Yet, the same patterns of regressivity can be observed, as the lowest income group sees a welfare loss of over 1.25% and the highest income group is 0.65%. The factor of regressivity is 1.9. Overall, the adverse distributional effects are also significantly larger under CF3 than under CF2. More importantly, again, the adverse distributional effects under CF3 compare favorably to the ones observed under CF1 while displaying a similar pattern of regressivity.

5.2. Effects of Energy Tax Reform on Revenue Recycling

In CF4, the extra tax revenues generated by the additional CO₂ taxation over what is needed to finance the energy tax reform are recycled in the economy through lower taxation at other tax margins. This means that this case, CF4 is strictly revenue neutral. Specifically, the recycling of additional revenue is conducted as follows: 50% for an investment tax credit, ITC hereafter, applicable to the traded goods sectors and 50% to reductions in personal income tax, IRS hereafter, divided into equal amounts across the different income groups; both mechanisms associated with broad energy efficiency gains.

5.2.1. Effects on Energy Markets and Emissions

Under CF4, energy prices increase by 3.72% and energy demand decreases by 4.47%. The price of electricity generation increases by 3.65%, which leads to a reduction of 1.75% in production. The production of electricity from renewable energy increases by 9.50%, while electricity imports increase by 6.06%. Overall, the share of electricity in final energy demand increases by 2.99%. Compared to CF3, the adverse effects on energy prices and demand are much smaller under CF4. This is particularly true for electricity prices and demand, which contributes to a much larger increase in the share of electricity in final energy demand.

Under CF4, CO₂ emissions decrease by 34.76%. This means that emissions by 2030 represent 55.1% of emissions in 2010, which is on target to meet the IPCC goal of 55% of 2010 levels. Emissions of the other GHG also decline substantially, except for HF and PF, which actually increase. Air pollutant emissions also fall significantly with the exception of NH₃. Compared with CF3, under CF4, we see less favorable emission reductions across the board. This is normal and it is a manifestation of the rebound effect. We allowed for a greater than necessary reduction in CO₂ emissions in CF3 to account for the rebound effect under recycling.

5.2.2. Macroeconomic and Distributional Effects

Under CF4, there is a 1.46% increase in GDP, with private investment increasing by 1.63% and employment by 0.90%. The CPI increases by 0.53% and private consumption increases by 1.18%. Foreign debt decreases by 0.90%, while public debt decreases by 3.59% due to the increase in economic activity. Compared to CF3, as desired, we observe a reversal of the adverse macroeconomic effects. Under CF4, there is an increase in production for most sectors. Electricity, mining, and rubber, however, are still affected adversely in a significant manner. This implies that while the recycling mechanisms have led to a reversion of the bulk of the adverse macroeconomic effects, there are still specific industries that need further consideration in terms of cost mitigation strategies.

Under CF4, household welfare gains are 1.09%. Furthermore, these effects are progressive in nature as the lower income group gains 2.51% while the highest income group gains just 0.53%. This means that under CF4, the adverse distributional effects both at the aggregate level and in terms of the regressive pattern that we observed under CF3 have been reversed.

5.2.3. On the Effects of Different Recycling Mechanisms

We now consider the decomposition of the CF4 scenario into its personal income tax and investment tax credit components in order to identify the mechanisms behind the overall CF4 results. Scenario CF4A considers carbon tax revenue recycling exclusively at the personal income tax level, while CF4B considers carbon tax revenue recycling exclusively through investment tax credits.

Recycling the additional CO₂ tax revenues after replacing the ISP at only the IRS level leads to the reversal of the negative distributional and regressive effects of the policy without reversing the adverse economic effects. Indeed, comparable emissions reductions leads to much greater welfare gains and much greater output losses. In turn, recycling the additional CO₂ tax revenues with a corporate income tax credit for private investment leads to the reversal of the negative economic impact of the policy without eliminating the negative and regressive distributional effects of the policy. Overall, these results indicate the need for a multifaceted recycling approach if the adverse economic and distributive effects of decarbonization are to be reversed.

6. Conclusions and Policy Implications

In this paper, we address the issue of energy taxation reform with an environmental focus in Portugal. We address this issue in the context of a dynamic disaggregated computable general equilibrium model of the Portuguese economy. We analyze the environmental, macroeconomic, and distributional effects of different policies allowing for current energy taxes to be replaced with a carbon tax while at the same time reaching the IPCC 2018 emissions reduction targets.

Our simulation results show, first, that a carbon tax of EUR 114 per ton imposed on top of the current energy taxation is enough to achieve the IPCC 2030 targets. It does so, however, at a high macroeconomic and distributional cost. In turn, replacing energy taxes with such a carbon tax would lead to smaller, although still significant, environmental effects and much smaller adverse macroeconomic and distributional effects.

This suggests that just replacing energy taxation with a carbon tax may be a good second-best alternative compared to the status quo. This is particularly so if political constraints do not allow for the implementation of a well-designed carbon tax with the proper recycling mechanisms. Just replacing the current energy taxes with a carbon tax would greatly mitigate the adverse economic and distributional effects of a stand-alone carbon tax, while still achieving important environmental goals in a context of strict tax revenue neutrality. In addition, this second-best alternative would improve the efficiency of the tax system by implicitly eliminating the myriad of perverse fossil fuel subsidies consigned in the current energy taxation system. Replacing the current energy taxation with a carbon tax completely sidesteps the politically charged issue of reducing or eliminating fossil fuel subsidies.

Our simulation results show, second, that to achieve the IPCC 2030 targets while replacing the current energy taxes ISP requires a carbon tax increasing to EUR 190 by 2030. The marginal burden of the additional tax in terms of the economic and distributional impact sharply increases compared to the previous cases. This suggests a pattern of sharply increasing marginal abatement costs.

Significantly, the case of achieving the IPCC targets while replacing the ISP with carbon taxation has similar CO₂ emissions effects compared to the case of adding carbon taxation to the ISP burden, as in this case. Yet, the economic and distributional effects are less adverse when the current energy taxes are replaced. This means that from a policy perspective, the strategy of replacing the current energy taxation with a carbon tax while at the same time reaching IPCC levels clearly dominates a strategy in which the IPCC levels are achieved by carbon taxation while maintaining the current patterns of energy taxation.

Finally, our simulation results show that proper recycling of revenues in excess of what is needed to replace current energy taxes allows for positive economic and distributional outcomes while keeping the environmental benefits, thereby reverting the adverse effect

observed. It is important to note that the recycling strategy presented in this paper is illustrative only. It is not the only way of achieving multiple dividends or the most desirable way to do so.

In this vein, we also show that the recycling of revenues through the demand side and personal income tax reductions are fundamental to achieving the desirable distributional effects of these policies, while the recycling of revenues through the supply side and investment tax credits are fundamental to achieving desirable macroeconomic outcomes.

Overall, our analysis indicates a clear specific path in the quest for decarbonization. First, replace current energy taxation with a carbon tax; second, target the carbon taxation levels necessary to achieve the relevant emissions goals; and third, use extra tax revenues to reverse any potential adverse macroeconomic and distributional effects of carbon taxation. In the process, this would be a way around the fossil fuel subsidies, which would effectively disappear.

Furthermore, our analysis indicates a clear framework for decarbonization efforts. There is no way to reach decarbonization without duly considering the potential adverse macroeconomic, budgetary, international competitiveness, and distributional effects of such policies. These adverse effects, if not addressed, would likely make it impossible to reach a political consensus on such policies. In this context, revenue neutrality—with its reduction in other tax distortions and the achievement of desirable economic and welfare outcomes—has to be the central piece of any decarbonization policies. As a corollary, addressing the issue of decarbonization in a comprehensive manner is of paramount importance. This is so because only with comprehensive reform will it be possible to neutralize such adverse effects. Piecewise measures are bound to lead to undesirable economic and welfare effects.

Naturally, there are several important extensions of the analysis in this paper. First, from a policy perspective, it would be important to develop a closer analysis of the effects of taxing all GHG emissions and not just CO₂ emissions in light of our evidence that the taxation of CO₂ emissions in and of itself affects other GHG emissions. In the same vein, and in the direction of a unified and comprehensive approach, it would be important to consider a comprehensive reform of all current environmental taxation including taxation of air pollutants and other environmental externalities, and not just of energy taxation. Second, it would be relevant to analyze the robustness of the magnitude of the effects of the different policies on different fossil fuel price scenarios. Different fossil fuel prices would differently affect emission projections, as well as the ability of the domestic economy, to counteract the adverse effects of decarbonization policies. Third, it would be informative to compare the effects on energy markets implied by these economic policies with the projections of decarbonization scenarios based on technological or engineering approaches that often inform actual energy policies. Fourth, it would be decisive from a policy perspective to model and analyze the interaction between the tax-based decarbonization strategies considered in this paper and other related policies, such as incentives for private investment in clean technologies or the development of new technologies based on the use of hydrogen.

Finally, although this is an energy policy paper applied to the Portuguese economy and its policy implications are directly relevant to the Portuguese case, its interest is far from parochial. The quest for decarbonization is universal. The existence of inefficient energy taxation mechanisms incorporating fossil fuel subsidies is widespread. The concerns over the macroeconomic and distributional effects of renewable energy finance and environmental policies, in general, are unavoidable if there is some hope of meaningful policies ever being adopted.

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Appendix A

Table A1. The dynamic general equilibrium model—the model structure.

The Production Sector	
$Y_t = A_t \left(\gamma_{va} VA_t^{\rho_{va}} + (1 - \gamma_{va}) AGG_E_t^{\rho_{va}} \right)^{\frac{1}{\rho_{va}}}$	(A1)
$VA_t = A_{va,t} \left(L_t^d HK_t \right)^{\theta_L} K_t^{\theta_K} KG_t^{1-\theta_L-\theta_K}$	(A2)
$K_{p,t+1} = (1 - \delta_K) K_{p,t} + I_{p,t} - \mu_K \frac{I_{p,t}^2}{K_{p,t}}$	(A3)
$NCF_t = Y_t - \left(1 + \tau_{fssc} \right) w_t \left(L_t^d HK_t \right) - I_{p,t} - I_{w,t} - (1 - \rho_I) \tau_{vat,I} I_{p,t} - p_{e,t} E_t - \tau_{cit} \left(Y_t - \left(1 + \tau_{fssc} \right) w_t \left(L_t^d HK_t \right) - \alpha I_{p,t} - \alpha I_{w,t} - p_{e,t} E_t \right) + \tau_{itc,I} I_{p,t} + \tau_{itc,RI} I_{w,t}$	(A4)
$\alpha = \left[1 - (1 + g)^{-NDEP} \right] / NDEP \left[1 - (1 + g)^{-1} \right]$	(A5)
$\theta_L \gamma_{VA} A_t \left(\gamma_{va} VA_t^{\rho_{va}} + (1 - \gamma_{va}) AGG_E_t^{\rho_{va}} \right)^{\frac{1}{\rho_{va}} - 1} VA_t^{\rho_{VA}} = (1 + \tau_{FSSC}) w_t L_t^d HK_t$	(A6)
$\frac{I_t}{K_t} = \frac{1}{2\mu_I} - [1 + (1 - \rho_I) \tau_{VAT,I} - \alpha \tau_{CIT} - \tau_{ITC}] (2\mu_I q_{t+1}^K)^{-1} (1 + r_{t+1})$	(A7)
$q_t^K = (1 - \tau_{CIT}) \theta_K \frac{Y_t}{K_t} + \frac{q_{t+1}^K}{1+r_{t+1}} \left[1 - \delta_K + \mu_I \left(\frac{I_t}{K_t} \right)^2 \right]$	(A8)
The Energy Sector	
$AGG_E_t = A_{E,t} \left(\gamma_E Crude Oil_t^{\rho_e} + (1 - \gamma_E) NTF_t^{\rho_e} \right)^{\frac{1}{\rho_e}}$	(A9)
$p_{e,t} E_t = p_{fe,t} FE_t + (p_{crude oil,t} + emission_factor_{oil} \tau_{carbon}) Crude Oil_t$	(A10)
$p_{fe,t} FE_t = \sum_{i=1}^n \left(p_{f,i,t} + emission_factor_f \tau_{carbon} \right) F_{i,t}$	(A11)
$\left(p_{f,i,t} + emission_factor_f \tau_{carbon} \right) \theta_{f,i} F_{i,t} - \left(p_{f,j,t} + emission_factor_f \tau_{carbon} \right) \theta_{f,j} F_{j,t} = 0$	(A12)
$\theta_E \frac{AGG_E_t}{FE_t} A_t \left(\gamma_{va} VA_t^{\rho_{va}} + (1 - \gamma_{va}) AGG_E_t^{\rho_{va}} \right)^{\frac{1}{\rho_{va}} - 1} (1 - \gamma_E) A_{E,t} \left(\gamma_E Crude Oil_t^{\rho_e} + (1 - \gamma_E) NTF_t^{\rho_e} \right)^{\frac{1}{\rho_e} - 1} NTF_t^{\rho_e} - p_{fe,t} = 0$	(A13)
$\frac{AGG_E_t}{Crude Oil_t} (1 - \gamma_{VA}) A_t \left(\gamma_{va} VA_t^{\rho_{va}} + (1 - \gamma_{va}) AGG_E_t^{\rho_{va}} \right)^{\frac{1}{\rho_{va}} - 1} \gamma_E A_{E,t} \left(\gamma_E Crude Oil_t^{\rho_e} + (1 - \gamma_E) NTF_t^{\rho_e} \right)^{\frac{1}{\rho_e} - 1} Crude Oil_t^{\rho_e} - p_{crude oil,t} = 0$	(A14)
$NTF_t = A_{E2,t} \left(\varphi_{cf} RK \right)_t^{\theta_{RK}} \prod_{i=1}^n F_{i,t}^{\theta_{f,i}}$	(A15)
$RK_{t+1} = (1 - \delta_{rk}) RK_t + I_{w,t} - \mu_{rk} \frac{I_{w,t}^2}{RK_t}$	(A16)
$\frac{I_{w,t}}{RK_t} = \frac{1}{2\mu_{rk}} - (1 + (1 - \rho_I) \tau_{vat,RI} - \alpha \tau_{cit} - \tau_{itcr}) (2\mu_{rk} q_{t+1}^{RK})^{-1} (1 + r_{t+1})$	(A17)
$q_t^{RK} = \frac{\partial \pi_t}{\partial RK_t} = (1 - \tau_{cit}) \theta_{RK} \frac{Y_t}{RK_t} + \frac{q_{t+1}^{RK}}{(1+r)} \left((1 - \delta_{rk}) + \mu_{rk} \left(\frac{I_{w,t}}{RK_t} \right)^2 \right)$	(A18)
$CarbonEmissions_t = \sum_f^N emission_factor_f F_{i,t} + emission_factor_{oil} Crude Oil_t$	(A19)
The Household Sector	
$U_{a,t} = \frac{\sigma}{\sigma-1} \sum_{v=0}^{\infty} \gamma^v \beta^v \left[c_{a+v,t+v}^{\frac{\sigma-1}{\sigma}} + B \ell_{a+v,t+v}^{\frac{\sigma-1}{\sigma}} \right]$	(A20)
$\sum_{v=0}^{\infty} \gamma^v [1 + (1 - \tau_r) r_{t+v}]^{-v} (1 + \tau_{VAT,C}) C_{a+v,t+v} = TW_{a,t}$	(A21)
$TW_{a,t} \equiv HW_{a,t} + FW_{a,t} + PVF_t$	(A22)
$HW_{a,t} = \sum_{m=0}^{\infty} \left(\frac{\gamma}{1 + (1 - \tau_r) r_{t+m}} \right)^m \left((1 - \tau_{pit}) ((1 - \tau_{wssc}) w_{t+m} (\bar{L} - \ell_{a+m,t+m}) HK_{t+m} + TR_{t+m}) + R_{t+m} - LST_{t+m} \right)$	(A23)

Table A1. Cont.

$FW_{a,t} = \left(1 + (1 - \tau_r)r_{t-1}^{pd}\right)PD_{t-1} + (1 - \tau_\pi)NCF_{t-1} - \left(1 + r_{t-1}^{fd}\right)FD_{t-1} +$	(A24)
$\left(1 - \tau_{pit}\right)\left((1 - \tau_{wssc})w_{t-1}(\bar{L} - \ell_{a-1,t-1})HK_{t-1} + TR_{t-1}\right) + R_{t-1} - LST_{t-1} - (1 + \tau_{vat})C_{a-1,t-1}$	
$(1 + \tau_{vat})C_t = \left[1 - (1 + (1 - \tau_r)r_{t-1})^{\sigma-1}\gamma\beta^\sigma\right](HW_t + (PD_t - FD_t) + PVF_t)$	(A25)
$\ell_t = \left(\frac{B(1+\tau_{vat})}{(1-\tau_{wssc})(1-\tau_{pit})w_t(1-UR_t)HK_t}\right)^\sigma C_t$	(A26)
The Public Sector	
$U_{public} = \sum_t \left[C_t \ell_t^{p_1}\right]^{\alpha_C} CG_t^{1-\alpha_C} (1 + (1 - \tau_r)r_t^{PD})^{-t}$	(A27)
$PD_{t+1} = (1 + r_t^{PD})PD_t + (1 + \tau_{vat,cg})CG_t + (1 + \tau_{vat,ig})IG_t + (1 + \tau_{vat,ih})IH_t + TR_t - T_t$	(A28)
$T_t = PIT_t + CIT_t + VAT_t + FSSC_t + WSSC_t + LST_t$	(A29)
$KG_{t+1} = (1 - \delta_{kg})KG_t + IG_t - \mu_{kg} \frac{IG_t^2}{KG_t}$	(A30)
$HK_{t+1} = (1 - \delta_{hk})HK_t + IH_t - \mu_{hk} \frac{IH_t^2}{HK_t}$	(A31)
$\frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_{t+1}^{PD})} = \frac{q_t^{PD}}{(1+(1-\tau_r)r_t^{PD})}$	(A32)
$q_{t+1}^{PD} = (1 - \alpha_C) \left(\frac{C_t \ell_t^{p_1}}{CG_t}\right)^{\alpha_C} (1 + (1 - \tau_r)r_t^{PD})$	(A33)
$-q_{t+1}^{PD} = q_{t+1}^{kg} \left(2\mu_{kg} \frac{IG_t}{KG_t}\right)$	(A34)
$q_t^{KG} = \frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_t^{PD})} \left((\tau_\pi(1 - \tau_{cit}) + \tau_{cit}) \frac{\partial Y_t}{\partial KG_t}\right) + \frac{q_{t+1}^{kg}}{(1+(1-\tau_r)r_{t+1}^{PD})} \left((1 - \delta_{kg}) + \mu_{kg} \left(\frac{IG_t}{KG_t}\right)^2\right)$	(A35)
$-q_{t+1}^{PD} = q_{t+1}^{hk} \left(2\mu_{hk} \frac{IH_t}{HK_t}\right)$	(A36)
$q_t^{HK} = \frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_t^{PD})} \left((\tau_{pit}(1 - \tau_{fssc}) - (1 - \tau_\pi)(1 + \tau_{cit})\tau_{fssc} + \tau_{wssc}) \frac{\partial Y_t}{\partial HK_t}\right) + \frac{q_{t+1}^{hk}}{(1+(1-\tau_r)r_{t+1}^{PD})} \left((1 - \delta_{hk}) + \mu_{hk} \left(\frac{IH_t}{HK_t}\right)^2\right)$	(A37)
Market Equilibrium	
$(1 - UR_t)LS_t = L_t^d$	(A38)
$Y_t = \sum_{i=1}^n p_{f,i,t}F_{i,t} + p_{crude\ oil,t}Crude\ Oil_t + C_t + I_{p,t} + I_{w,t} + CG_t + IG_t + IH_t - NX_t$	(A39)
$FD_{t+1} = (1 + r_t^{fd})FD_t + NX_t - R_t$	(A40)
$FW_t = PD_t - FD_t$	(A41)

Table A2. The dynamic general equilibrium model—the basic data set.

Domestic spending data (% of Y_0)		
Y_0	GDP (billion Euros)	166.2279
g_0	Long-term growth rate (%)	0.01763
VA_0	Value added	83.743
AGG_E_0	Primary energy consumption expenditure	2.557
C_0	Private consumption	62.263
$I_{p,0}$	Private investment	20.312
$I_{w,0}$	Private wind investment	0.064
CG_0	Public consumption	14.652
IG_0	Public capital investment	3.411
IH_0	Public investment in education	6.996
Primary energy demand (GJ as a % of Y_0)		
E_0	Primary fossil energy spending	2.472
NTF_0	Non-transportation fuels	0.584
FE_0	Fossil fuels (excluding crude oil)	0.160
$CrudeOil_0$	Quantity of crude oil imports	0.321
$F_{Coal,0}$	Quantity of coal imports	0.082
$F_{Natural\ Gas,0}$	Quantity natural gas imports	0.077

Table A2. Cont.

Energy prices (€ per GJ)		
$p_{Crude\ Oil,0}$	Import price of crude oil	6.14
$p_{f,Coal,0}$	Import price of coal	1.89
$p_{f,Natural\ Gas,0}$	Import price of natural gas	4.45
Foreign account data (% of Y_0)		
NX_0	Trade deficit	7.697
$r_0^{FD} FD_0$	Interest payments of foreign debt	3.157
R_0	Unilateral transfers	11.413
CAD_0	Current account deficit	1.913
FD_0	Foreign debt	108.500
Public sector data (% of Y_0)		
T_0	Total tax revenue	41.958
PIT_0	Personal income tax revenue	5.710
CIT_0	Corporate income tax revenue	3.110
VAT_0	Value-added tax revenue	13.700
VAT_c	On private consumption expenditure	10.669
VAT_i	On private investment expenditure	1.902
VAT_{cg}	On public consumption expenditure	0.649
VAT_{ig}	On public capital investment expenditure	0.379
VAT_{ih}	On public investment in human capital	0.101
$WSSC_0$	Social security tax revenues	11.700
$WSSC_{1,0}$	Employers' contributions	5.600
$WSSC_{2,0}$	Workers' contributions	6.100
$Carbon\ Tax_0$	CO ₂ tax	0.000
LST_0	Lump sum tax revenue	7.738
TR_t	Social transfers	15.915
$r_0^{PD} PD_0$	Interest payments of public debt	2.497
DEF_0	Public deficit	0.015
PD_0	Public debt	85.800
Population and Employment Data (% of POP_0)		
POP_0	Population (in thousands)	10.586
L_0	Active population	5.587
UR_0	Unemployment rate	0.058
Private wealth (% of Y_0)		
HW_0	Human wealth	2574.498
FW_0	Financial wealth	−22.700
PVF_0	Present value of the firm	1429.101
NCF_0	Distributed profits	17.930
Prices		
w_0	Wage rate	0.031
q_0^{PD}	Shadow price of public debt	−0.883
q_0^k	Shadow price of private capital	1.291
q_0^{rk}	Shadow price of wind energy capital	1.291
q_0^{kg}	Shadow price of public capital	1.104
q_0^{hk}	Shadow price of human capital	5.521

Table A2. Cont.

Capital stocks (% of Y_0)		
K_0	Private capital	215.321
RK_0	Wind energy capital stock	1.142
KG_0	Public capital stock	73.415
HK_0	Human capital stock	226.899

Table A3. The dynamic general equilibrium model—the structural parameters.

Household Parameters		
β	Discount rate	0.003
γ	Probability of survival	0.987
g_{POP}	Population growth rate	0.000
σ	Elasticity of substitution	1.000
p_1	Leisure share parameter—C	0.331
Production parameters		
θ_L	Labor share in value-added aggregate—C	0.506
θ_{KP}	Capital share in value-added aggregate—C	0.294
θ_{KG}	Public capital share in value-added aggregate—C	0.200
σ_{VA}	Elasticity of substitution between value-added and energy	0.400
σ_{Crude}	Elasticity of substitution between oil and other energy	0.400
θ_{KR}	wind energy share in non-transportation fuels—C	0.146
θ_E	fossil energy share in non-transportation fuels—C	0.854
φ_{cf}	Wind energy price: quantity capacity utilization factor—C	0.074
θ_{Coal}	coal share in non-transportation fuels—C	0.313
θ_{gas}	natural gas share in non-transportation fuels—C	0.687
γ_{VA}	CES scaling share between value-added and energy—C	1.000
γ_E	CES scaling share between oil and other energy—C	0.580
δ_k	Depreciation rate—private capital—C	0.060
μ_k	Adjustment costs coefficient—private capital—C	1.159
δ_{Rk}	Depreciation rate—wind energy capital—C	0.028
μ_{Rk}	Adjustment costs coefficient—wind energy capital—C	1.952
$\dot{A}_i / A_i$	Exogenous rate of technological progress	0.000
Emission factor		
$emission_factor_{oil}$	Emission factor for oil (tCO ₂ per TJ)	72.600
$emission_factor_{coal}$	Emission factor for oil (tCO ₂ per TJ)	90.200
$emission_factor_{gas}$	Emission factor for oil (tCO ₂ per TJ)	55.800
Public Sector Parameters—Tax Parameters		
τ_{pit}	Effective personal income tax rate	0.104
τ_{π}	Effective personal income tax rate on distributed profits	0.112
τ_r	Effective personal income tax rate on interest income	0.200
τ_{cit}	Effective corporate income tax rate	0.116
$NDEP$	Time for fiscal depreciation of investment	16.000
α	Depreciation allowances for tax purposes	0.735
ρ_I	Fraction of private investment that is tax exempt	0.680
$\tau_{itc,I}$	Investment tax credit rate—private capital	0.005
$\tau_{itc,RI}$	Investment tax credit rate—wind energy capital	0.005
$\tau_{VAT,C}$	Value-added tax rate on consumption	0.212
$\tau_{vat,I}$	Value-added tax rate on investment	0.094
$\tau_{vat,cg}$	Value-added tax rate on public consumption	0.044
$\tau_{vat,ig}$	Value-added tax rate on public capital investment	0.111
$\tau_{vat,ih}$	Value-added tax rate for public investment in human capital	0.014
τ_{fssc}	Firms' social security contribution rate	0.152
τ_{wssc}	Workers' social security contribution rate	0.166

Table A3. Cont.

Public Sector Parameters—Outlay Parameters		
$1 - \alpha_C$	Public consumption share	0.215
δ_{kg}	Public infrastructure depreciation rate—C	0.020
μ_{kg}	Adjustment cost coefficient—C	2.392
δ_{hk}	Human capital depreciation rate—C	0.000
μ_{hk}	Adjustment cost coefficient—C	13.817
Real interest rates		
r, r^{FD}, r^{PD}	Interest rate	0.0291

C indicates the calibrated parameter.

Table A4. The dynamic general equilibrium model—model variables.

Stock Variables	
K_t	Private Capital
RK_t	Wind Energy Capital
KG_t	Public Capital
HK_t	Human Capital
PD_t	Public Debt
FD_t	Foreign Debt
$FW_{a,t}$	Financial Wealth
$HW_{a,t}$	Human Wealth
Shadow Prices	
q_t^K	Shadow Price of Private Capital
q_t^{RK}	Shadow Price of Wind Energy Capital
q_t^{KG}	Shadow Price of Public Capital
q_t^{HK}	Shadow Price of Human Capital
q_t^{PD}	Shadow Price of Public Debt
Production Variables	
Y_t	Gross Domestic Product
VA_t	Value Added
L_t^d	Labor Demand
$I_{p,t}$	Private Investment
PVF_t	Present Value of the Firm
NCF_t	Net Cash Flow
Energy Variables	
AGG_E_t	Aggregate Energy
NTF_t	Primary Demand for Non-transportation Fuels
E_t	Fossil Fuel Demand
FE_t	Fossil Fuels Composite (Excluding Crude Oil)
$Crude\ Oil_t$	Primary Demand for Crude Oil
$F_{i,t}$	Fossil Fuels (Excluding Crude Oil), where $i = coal, natural\ gas$
$I_{W,t}$	Private Investment in Wind Energy
Household Variables	
C_t	Private Consumption
ℓ_t	Leisure
LS_t	Labor Supply
$TW_{a,t}$	Total Wealth

Table A4. Cont.

Public Sector Variables	
CG_t	Public Consumption
IH_t	Human Capital Investment
IG_t	Public Capital Investment
T_t	Total Tax Revenue
PIT_t	Personal Income Tax Revenue
CIT_t	Corporate Income Tax Revenue
VAT_t	Value-Added Tax Revenue
$FSSC_t$	Firms' Social Security Contributions
$WSSC_t$	Workers' Social Security Contributions
LST_t	Lump Sum Tax Revenue

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