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ON THE MACROECONOMIC AND DISTRIBUTIONAL EFFECTS OF THE REGULATED CLOSURE OF COAL-OPERATED POWER PLANTS [*]

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This article examines the economic, distributional and environmental impacts of the regulated early closure of coal-fired power plants in Portugal using a multi-sector and multi-household dynamic computable general equilibrium model. The closure of the power plants has positive and significant environmental effects. It results, however, in an increase in electricity prices, which, in turn, leads to detrimental macroeconomic and distributional effects. We argue that a carbon tax with the same environmental impact would have substantial conceptual, pragmatic and pedagogical advantages over regulated early plant closures. It would generate the tax revenues necessary to mitigate or reverse the adverse macroeconomic and distributional effects. Regulated early closures could be a good second best alternative if there is no political will for or consensus on the implementation of a proper carbon tax with adequate revenue recycling. In any case, these plant closures are far from leading to the reductions in emissions established by the IPCC and adopted by the Portuguese authorities.

Keywords: Dynamic General Equilibrium, Coal-operated Power Plants, Regulated Closures, Macroeconomic Effects, Distributional Effects, Environmental Effects, Portugal
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1. INTRODUCTION

In late 2017, the Portuguese Government announced the mandatory closure of all coal-fired power plants in the country by 2030. This article examines the economic,

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budgetary, distributional, and environmental impacts of such regulated closures using a multi-sector and multi-household dynamic general equilibrium model of the Portuguese economy.

Portugal has two large coal-fired power plants, one in Sines and the other in Pego. The Sines plant was commissioned in 1985, has a capacity of 1192 MW, and is operated by Energias de Portugal (EDP). The Pego plant was commissioned in 1993, it has a capacity of 628 MW and is operated by Tejo Energia, a joint venture between TrustEnergy and Endesa Generation. These two plants play a major role in the Portuguese energy system. Production of electricity from coal accounted for 26% of the electricity generated in 2017: 18% from Sines and 8% from Pego (DGEG, 2018). These power plants account for more than half of thermal production of electricity with natural gas accounting for the remainder. In addition, coal-fired units are a substantial component of electric power operators generating portfolios. In 2017, the production of electricity from coal in Sines accounted for about 12.5% of the electricity produced by EDP and the production of electricity from coal in Pego accounted for about 42.7% of the electricity produced by Endesa (EDP, 2018).

The environmental impact of these coal-fired power plants is very substantial. In 2017, Sines and Pego accounted for 19.1% of carbon dioxide emissions in Portugal. In fact, they were the two largest individual contributors to greenhouse gases emissions in the country (APA, 2018). Therefore, it is not surprising that increasing efforts of environmental groups and increasing awareness by the policy makers ultimately translated into the regulated early closure of the two power plants by 2030.

While the environmental motivation for the regulated early closure of the two coal-fired power plants is understandable, some critical questions remain. First, these are regulated early closures. The facilities could still operate in a cost-effective manner and, therefore, early closures lead to higher costs of production and ultimately higher electricity prices. These, in turn, reverberate throughout the economy with adverse macroeconomic and distributional effects. Second, as the objective of the regulated early closures is the reduction in emissions, it remains to be established that, from a macroeconomic and distributional perspective, that is the best strategy. It is important to ascertain how the effects of such early closures compare, for example, to the effects of a carbon tax leading to the same reduction in emissions.

The literature on the macroeconomic and distributional effects of regulated early closures of coal-fired power plants is surprisingly scant. It is surprising because there is a very large number of power plants scheduled for regulated early closure in several EU countries, Canada, Israel, Mexico, New Zealand, etc. (see, for example, Jewell et al. (2019)). In addition, higher electricity prices will ensue from such closures and the corresponding economic and distributional impacts are inevitable and may be substantial depending on the role of such power plants in the generation system in the country.

There is a relatively small literature on the effects of closures of coal-fired as well as on the effects of closures of nuclear power plants - although not necessary regulated early closures. Some of the literature deals with issues somewhat related to our focus.

Some papers discuss the extent to which coal-fired power plants are used under the changing influence of climate policy (see, for example, Kloosterhuis and Mulder, 2015; Mulder and Pangan, 2017). Other papers, deal with market mechanisms to deal with the energy effects of closures (see, for example, Jotzzo and Mazzouz, 2015; Davis and Hausman, 2016). Still other papers focus on the regional economic impacts of closures on unemployment or housing markets (see for example Bauer et al., 2017; Haller et al., 2017; Jolley et al., 2019; Burke et al., 2019). Finally, other papers deal with the international challenges closures play in a path for deep decarboniation (see, for example, Kefford et al., 2018).

There are two papers, which come close to our focus. Reitz et al. (2014), focus on the impact on electricity prices of early closure of coal-fired power plants in Germany. In turn, Bockermann et al. (2006) deal with the long-term macroeconomic effects of early decommissioning of a nuclear power plant in Bulgaria. Yet, none of these studies addresses the overall macroeconomic and distributional implications of regulated early closures and the case of coal-fired power plants.

The objective of this research is to examine the environmental, macroeconomic and distributional effect of the regulated early closure of the two coal-fired power plants in Portugal. The scheduled closure of coal-operated power plants represents a negative supply shock in the electricity market, leading to higher equilibrium electricity prices with repercussions that reverberate throughout the economy. The increase in electricity prices will depend on how these closures affect the merit order for plants supplying electricity to the grid, as well as the patterns of demand for electricity in the system by businesses and households. The macroeconomic and distributional impacts of these scheduled closures depend ultimately on how they affect the costs of production across different sectors of economic activity and expenditure patterns across different household groups.

We address these research questions in the context of a multi-sector, multi-household dynamic computable general equilibrium model of the Portuguese economy. From a methodological perspective, this work is based on a newly-developed disaggregated dynamic general equilibrium model that builds upon the aggregate dynamic general equilibrium model of the Portuguese economy, known as DGEP. Previous versions of this model are documented in Pereira and Pereira (2014c), and have been used recently to address energy and climate policy issues (see Pereira and Pereira, 2014a, 2014b, 2014c, 2017a, 2017b, 2017c; Pereira et al., 2016). This model has a detailed description of the tax system and a relatively fine differentiation of consumer and producer goods, particularly those with a focus on energy products. Household heterogeneity in income and consumption patterns is captured by differentiating among five household groups.

General equilibrium models have been extensively used in energy studies. For general surveys see Bhattacharyya (1996) and Bergman (2005) and for a discussion of the merits and concerns with this approach see Sbordone et al. (2010) and Blanchard (2016). Our model follows in the tradition of the early models developed by Borges and

Goulder (1984) and Ballard, Fullerton, Shoven and Whalley (2009) while in its specifics is more directly linked to the recent contributions of Goulder and Hafstead (2013), Bhattarai et al. (2016), Tran and Wende (2017), and Annicchiarico et al. (2017).

The remainder of this article proceeds as follows. Section 2 provides a brief description of the disaggregated dynamic general equilibrium model. Section 3 presents the principal results of our analysis of the effect of closing these coal fired power plants as scheduled in 2030. Section 4 compares the effects of the regulated early closures to the effects of a carbon tax yielding the same emissions reductions. Finally, Section 5 provides a summary, policy implications, and concluding thoughts.

2. THE DYNAMIC COMPUTABLE GENERAL EQUILIBRIUM MODEL

What follows is a very brief and general description of the design and implementation of the new multi-sector, multi-household dynamic computable general equilibrium model of the Portuguese economy. See Pereira and Pereira (2017d) for further details. In addition, we include Figure 1 and Figure 2 which show the general inter-connections of the model and of its energy module, respectively, as well as the mathematical details of the aggregated version of the model.

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 a foreign sector. All agents and the economy in general face financial constraints that frame their economic choices. All agents are price takers and are assumed to have perfect foresight. With money absent, the model is framed in real terms.

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.

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 thirteen 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.

All economic agents interact through demand and supply mechanisms 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.

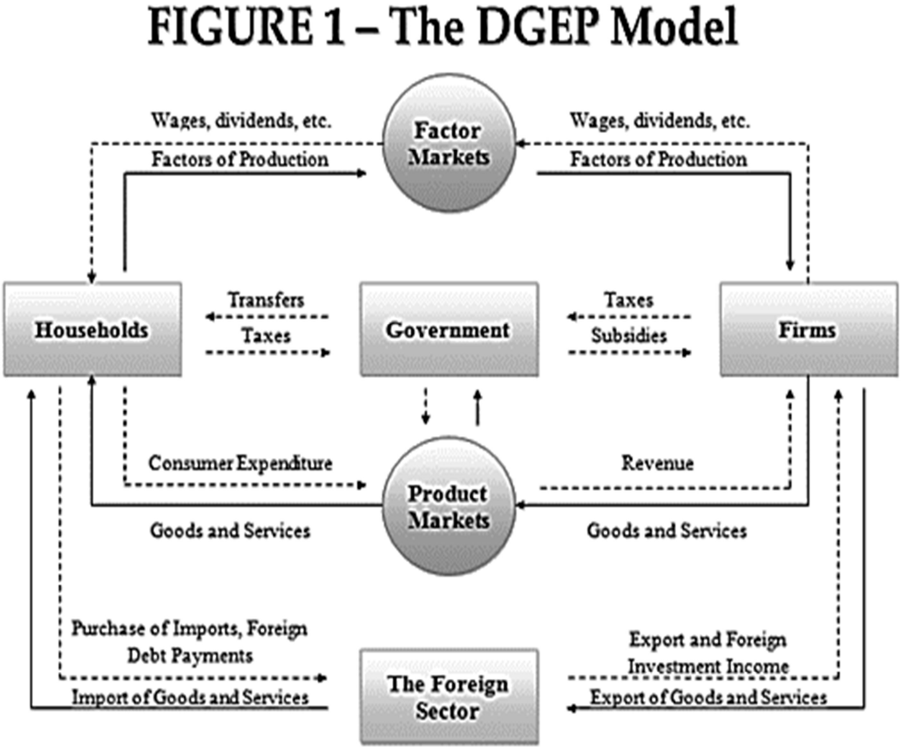

Figure 1. The DGEP Model

The total labor supplied by the different households, adjusted by an unemployment rate that is assumed exogenous and constant, must equal 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 equal 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. In addition, the evolution of the stocks of public debt and of the foreign debt act as resource constraints in the overall economy. The endogenous and optimal changes in these stock variables – investment, saving, the budget deficit, and current account deficit – provide the link between subsequent time periods. Accordingly, the model can be conceptualized as a large set of nonlinear difference equations, where flow variables are determined through optimal control rules.

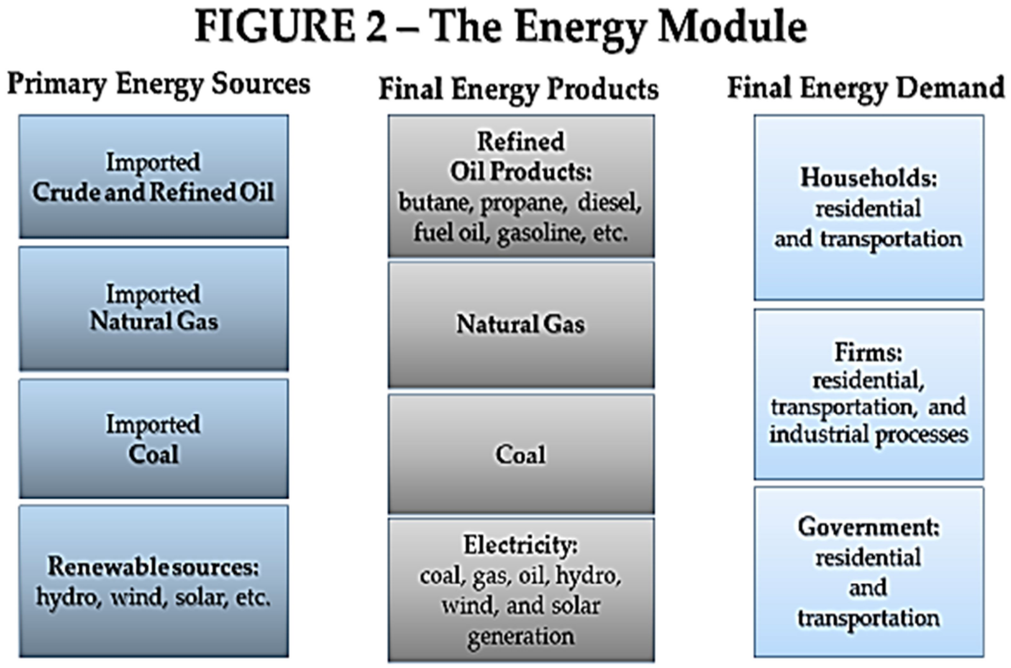

Figure 2. The Energy Module

The intertemporal path for the economy is described by the behavioral equations, the equations of motion of 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 prices 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 marginal effects of any policy or exogenous change, as deviations from the base case.

There are three types of calibration restrictions imposed by the existence of a steady state. 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 of the respective type 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.

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.

3. ON THE EFFECTS OF THE SCHEDULED CLOSURE IN 2030

3.1. Reference Case, Counterfactual Scenarios and Simulation Design

The reference case for our simulations is obtained from this steady state trajectory by incorporating into it international fossil fuel price and CO2 price scenarios. These scenarios are based on the information in the World Energy Outlook by the International Energy Agency for the fossil fuel price, and from the Bloomberg News Energy Finance for carbon prices. Furthermore, the reference case assumes that coal-fired power plants are operational indefinitely. In turn, the counterfactual scenario is designed account for the scheduled closure of Sines and Pego in 2030.

We present the simulation results as percent deviations from the model simulations in the reference scenario. We focus mostly on the effects observed by 2040, which we will refer to as the long-term effects. We focus on the impact of the scheduled closure in four main domains. First, we consider the effects on the energy sector in general and the electricity market in particular, including impact on CO2 emissions. Second, we identify the macroeconomic effects, including GDP, prices, employment, investment, as well as the public sector and foreign sector accounts. Third, we analyze the industry specific effects, output and employment as well as exports. Finally, we focus on the distributional welfare effects across different household groups.

Lastly, as the price of electricity plays such a critical role in our analysis, and given the different notions prevalent in the literature as to what they represent, it is important to clarify the exact meaning of electricity prices in general equilibrium. In our model, electricity prices are market-clearing prices under general competitive market assumptions.

Electricity prices reflect equilibrium conditions and therefore a balance between supply and demand conditions. Ultimately, they can be conceptualized as average production prices for the amounts of electricity produced under the prevailing market demand conditions.

On the supply side, prices reflect all costs of production: capital, labor, energy, and materials. Because of the dynamic nature of the model, all stocks have fixed costs in the short term but are variable in the long term. On the demand side, prices reflect fuel substitution effects by households and businesses as well as higher production costs by businesses across all sectors of economic activity. They reflect income effects and losses in purchasing power by households due to higher prices across sectors of economic activity and feedbacks that affect consumers' budget constraints.

3.2. Effects on the Electricity Market

We report the effects on electricity prices and electricity market in Tables 1 and 2. Our simulation results suggest that the scheduled closures lead to an increase in the price of electricity of 7.2% in 2040. Domestic production of electricity decreases 5.6% in

2040 relative to the reference scenario. This reduction is driven by a 37.1% reduction in thermal power generation due to the closures. The production of electricity from natural gas increases by 2.1% and the production of electricity from renewable energy systems increases by 1.5%. In order to satisfy domestic electricity demand, the decline in domestic production goes hand in hand with an increase in imported electricity. Net imports of electricity increase 34.6% in 2040 relative to the reference scenario.

Table 1. Effects on Final Energy Prices

Percent Change from Baseline

	2020	2025	2030	2035	2040
Total Final Energy Price	-0.048	-0.112	3.088	3.093	3.119
Propane	-0.018	-0.043	0.824	0.827	0.836
Butane	-0.010	-0.028	0.176	0.158	0.146
LPG	-0.053	-0.112	2.409	2.406	2.423
Fuel Oil	-0.024	-0.059	0.842	0.825	0.818
Gasoline	-0.003	-0.007	0.020	0.020	0.021
Diesel	-0.002	-0.006	0.037	0.036	0.036
Electricity	-0.105	-0.241	7.121	7.140	7.206
Biomass	-0.195	-0.457	0.937	0.616	0.404

Table 2. Effects on Electricity Markets

Percent Change from Baseline

	2020	2025	2030	2035	2040
Electricity Production	0.079	0.186	-5.526	-5.545	-5.599
Thermal Generation	-0.018	-0.036	-36.144	-36.633	-37.097
Natural Gas	-0.039	-0.087	2.104	2.103	2.116
Renewable Energy Systems	0.206	0.477	0.873	1.234	1.504
Net Electricity Imports	-0.541	-1.130	34.174	34.256	34.551
Electricity Demand	0.065	0.151	-4.506	-4.522	-4.565
Electricity Demand by Households	0.048	0.117	-3.615	-3.628	-3.662
First Quintile (lowest income)	0.052	0.122	-3.644	-3.660	-3.696
Second Quintile	0.052	0.125	-3.853	-3.868	-3.904
Third Quintile	0.050	0.121	-3.780	-3.794	-3.829
Fourth Quintile	0.047	0.116	-3.627	-3.641	-3.675
Fifth Quintile (highest income)	0.042	0.105	-3.277	-3.287	-3.316
Electricity Demand by Firms	0.076	0.175	-5.221	-5.243	-5.296
ETS	0.071	0.165	-4.994	-5.015	-5.067
Non-ETS	0.108	0.244	-6.767	-6.786	-6.847
% Electricity in Final Energy Demand	0.039	0.086	-3.495	-3.532	-3.583

On the demand side, we observe a reduction in electricity demand by residential, commercial and industrial users due to higher equilibrium electricity prices. Electricity demand by households is 3.7% lower in 2040 than in the reference scenario and demand by businesses is 5.3% lower. Overall, electricity demand decreases by 4.6% in 2040 than in the reference scenario.

The reductions in electricity demand by households decreases with income, reflecting the diminished share of electricity in household expenditures. The exception to this regressive pattern is the very lowest income quintile, a pattern that reflects the lower accessibility to electricity services by the lowest income group as well as more muted labor supply response among households in the lowest income bracket.

Finally, where possible, one would expect both businesses and households to substitute other forms of energy for electricity, thereby leading to a reduced share of electricity in the overall energy market. Overall, the contraction in the electricity market translates by 2040 into a loss of 3.6% in the share of electricity in final energy demand.

3.3. Effects on Final Energy Markets

The effects on final energy and CO2 emissions are reported in Tables 3 and 4. Higher electricity prices affect other final energy prices and, thereby, energy markets more broadly through two important channels. First, electricity consumption in the petroleum refining makes up a small, but important part of the costs of production. The increase in production costs will increase the prices for petroleum products. Second, business demand and household demand responses, influenced by the increase in costs as well as inter-fuel substitution options, will play a large role in determining the overall effect of the plant closures on energy demand.

We start by observing that, as it is clear from Table 1, the increase in electricity prices induces an increase across the board of the prices of the other final energy products. The largest increase in prices is for LPG with an increase of 2.4% by 2040 and to a lesser extent fuel oil and propane with an increase of 0.8%. The effects on butane, gasoline, and diesel are marginal as the latter two are largely transportation fuels that do not satisfy the same energy services demand as electricity.

Final energy demand decreases by 2.1% in 2040 relative to the reference scenario. Energy demand by firms decreases by 4.8%, led by a 5.9% reduction in the ETS sectors, while final demand for energy by households decreases by 1.4%. As a reminder, electricity demand by firms decreases by 5.3% and by households by 3.7%. Accordingly, in both cases, the reduction in energy demand reflect a shift away from electricity to other sources of energy coupled with income responses that depress overall demand. Households have a relatively high degree of flexibility in replacing electric power systems used in heating and in cooking with wood, natural gas and petroleum products.

From a distributional perspective, we observe a regressive pattern of demand responses for final energy demand across all income groups. The overall reduction in final energy demand are much smaller than the reductions in final electricity demand.

The regressive nature of these final energy demand responses, however, is much more pronounced. The reduction in demand for the highest income group is 33% smaller than that for the lowest income group compared to just 10% smaller response for the highest income group for electricity demand.

Table 3. Effects on Final Energy Demand

Percent Change from Baseline

	2020	2025	2030	2035	2040
Final Energy Demand	0.032	0.078	-2.064	-2.067	-2.084
Energy Demand by Households	0.020	0.055	-1.441	-1.437	-1.444
First Quintile (lowest income)	0.029	0.073	-1.840	-1.840	-1.854
Second Quintile	0.024	0.064	-1.535	-1.528	-1.534
Third Quintile	0.021	0.058	-1.442	-1.435	-1.440
Fourth Quintile	0.018	0.052	-1.380	-1.377	-1.384
Fifth Quintile (highest income)	0.014	0.042	-1.244	-1.243	-1.250
Energy Demand by Firms	0.046	0.109	-4.678	-4.711	-4.764
ETS	0.050	0.120	-5.799	-5.848	-5.917
Non-ETS	0.037	0.084	-2.032	-2.032	-2.046

Table 4. Effects on CO2 Emissions

Percent Change from Baseline

	2020	2025	2030	2035	2040
Total CO_2 Emissions	-0.004	-0.009	-21.447	-21.737	-22.015
Households	-0.010	-0.016	0.348	0.350	0.355
Residential	-0.033	-0.068	1.652	1.652	1.665
Transportation	-0.003	-0.001	-0.029	-0.025	-0.022
Households	-0.010	-0.016	0.348	0.350	0.355
First Quintile (lowest income)	-0.007	-0.014	0.401	0.401	0.404
Second Quintile	-0.011	-0.020	0.485	0.487	0.493
Third Quintile	-0.012	-0.020	0.454	0.457	0.464
Fourth Quintile	-0.010	-0.016	0.343	0.345	0.350
Fifth Quintile (highest income)	-0.008	-0.010	0.188	0.192	0.197
Production Sectors	-0.002	-0.007	-28.690	-29.079	-29.452
ETS	-0.009	-0.019	-42.111	-42.684	-43.231
Non-ETS	0.011	0.018	-0.171	-0.169	-0.170

Discontinuing the use of coal in the production of electricity in Portugal can contribute towards a very substantial reduction in carbon dioxide emissions. CO2 emissions are 22.0% lower than in the reference scenario in 2040. Not surprisingly, the reduction in CO2 emissions stem primarily from eliminating the use of coal in electricity generation. Emissions reductions among other industrial sectors of economic activity, particularly those not energy-intensive, are rather modest and mostly due to contractionary income effects. In turn, household emissions increase, although just marginally, due to an increase in residential emissions as household rely more heavily on natural gas for cooking and heating. From a distributional perspective, the reductions in CO2 emissions reflect a greater relative level of effort among lower income households in their contribution towards domestic emissions reductions goals, a result that is reflective of the regressive nature of this policy.

3.4. Macroeconomic Effects

The macroeconomic effects are reported in Table 5. The macroeconomic effects of higher electricity price depend on the increase in production costs in each sector of economic activity, the extent to which these increases in production costs are going to induce higher prices for customers, and on the demand responses. An increase in electricity costs induces businesses to reduce electricity consumption and changes their production structure to rely more heavily on other energy inputs, workers and energy-efficient capital equipment.

Table 5. Macroeconomic Effects

Percent Change from Baseline

	2020	2025	2030	2035	2040
GDP	0.008	0.014	-0.514	-0.543	-0.572
Private Consumption	-0.004	-0.001	-0.133	-0.138	-0.143
Investment	0.063	0.089	-0.094	-0.108	-0.123
Employment	0.007	0.010	-0.169	-0.182	-0.194
CPI	-0.003	-0.008	0.265	0.281	0.295
Foreign Debt	0.008	0.020	0.035	0.380	0.738
Trade Deficit	0.054	0.075	1.454	1.591	1.716
Exports	-0.011	-0.024	-0.778	-0.853	-0.921
Imports	0.003	-0.001	-0.254	-0.266	-0.276
Public Debt	-0.002	-0.010	-0.026	0.835	1.892
Public Expenditures	-0.003	-0.008	0.252	0.335	0.430
Tax Revenue	0.000	-0.001	-0.245	-0.242	-0.238

The scheduled closure of the coal-operated power plants in 2030 reduces GDP in 2040 by 0.6% relative to the references scenario. This reduction is driven by reductions in private consumption of 0.1% and exports by 0.9%, and to a lesser extent in private investment. In addition, employment decreases by 0.2% relative to the reference scenario and consumer prices increase by 0.3%. Overall, the effects of the scheduled closures have a negative effect on macroeconomic performance.

In terms of the foreign accounts, the lower level of exports in goods and services leads to a deterioration in the trade deficit by 1.7%, despite the small reduction in imports induced by the contraction in economic activity and domestic demand. In the long term, the foreign debt to GDP ratio increases by 0.7%.

Finally, the effects on the public sector account are detrimental as well. We observe a 1.9% increase in the public debt to GDP ratio by 2040 relative to the reference scenario. This is partially due to rigidities in public spending and the higher cost of goods and services. More importantly, it is due to the persistent reduction in tax revenues of 0.2% driven by contracting tax bases in light of weaker economic performance.

3.5. Industry Effects

The industry effects are reported in Tables 6 and 7. The adverse aggregate effects of the scheduled closures on GDP reflects reductions in production activity across the board. Naturally, electricity is the sector that is affected the most with a decline of 5.6% by 2040 compared to the reference scenario. Other sectors significantly affected are equipment manufacturing, wood, pulp, and paper, rubber, plastic and ceramics, and primary metals. We also identify significant negative effects for the manufacturing of textiles, and chemicals and pharmaceuticals. The effects on petroleum refining, construction, and other sectors are marginal.

In turn, biomass is the only sector that experiences an increase in production. This is due to households substituting away from electricity for cooking and heating. This sector suffered therefore a typical demand shock resulting in higher prices as well as higher equilibrium quantities.

The effects on international competitiveness through their impact on exports are also widely felt. Naturally, exports of electricity are substantially lower than in the reference scenario. In addition, the sectors that are most affected by these scheduled closures are primary traded goods sectors – equipment, textiles, wood, pulp and paper, chemicals and pharmaceuticals, rubber, plastic, and ceramics, and primary metals. These are all fairly energy intensive, in particular electricity intensive sectors. They represent just 11% of the domestic production but account for over 50% of the exports. This reduction in exports contributes directly to the overall deterioration of the foreign account position induced by the scheduled closure of the coal-operated power plants, as discussed above.

Table 6. Effects on Output by Industry

Percent Change from Baseline

	2020	2025	2030	2035	2040
Economy-wide	0.008	0.014	-0.514	-0.543	-0.572
Petroleum Refining	0.005	0.012	-0.032	-0.028	-0.026
Electricity Production	0.079	0.186	-5.526	-5.545	-5.599
Biomass	0.128	0.308	0.831	1.095	1.281
Agriculture	-0.001	-0.003	-0.310	-0.343	-0.374
Equipment Manufacturing	-0.078	-0.179	-1.062	-1.262	-1.435
Construction	0.054	0.077	-0.103	-0.117	-0.132
Transportation	-0.001	-0.002	-0.270	-0.298	-0.326
Textiles	0.013	0.035	-0.662	-0.677	-0.699
Wood, pulp and paper	-0.028	-0.065	-1.286	-1.398	-1.499
Chemicals and pharmaceuticals	0.011	0.027	-0.881	-0.911	-0.944
Rubber, plastic and ceramics	-0.002	-0.013	-1.078	-1.155	-1.226
Primary metals	-0.022	-0.054	-1.261	-1.372	-1.473
Other	0.004	0.007	-0.127	-0.148	-0.167

Table 7. Effects on Exports by Industry

Percent Change from Baseline

	2020	2025	2030	2035	2040
Economy-wide	-0.011	-0.024	-0.778	-0.853	-0.921
Petroleum Refining	0.008	0.020	-0.078	-0.073	-0.071
Electricity Production	0.511	1.185	-28.874	-28.940	-29.162
Biomass					
Agriculture	-0.004	-0.007	-0.478	-0.536	-0.590
Equipment Manufacturing	-0.091	-0.208	-1.184	-1.411	-1.609
Construction	0.042	0.061	-0.194	-0.225	-0.253
Transportation	-0.002	-0.002	-0.389	-0.435	-0.478
Textiles	0.020	0.051	-0.939	-0.963	-0.998
Wood, pulp and paper	-0.041	-0.092	-1.715	-1.869	-2.008
Chemicals and pharmaceuticals	0.017	0.043	-1.228	-1.268	-1.313
Rubber, plastic and ceramics	-0.009	-0.026	-1.439	-1.543	-1.640
Primary metals	-0.028	-0.065	-1.529	-1.661	-1.782
Other	0.003	0.007	-0.191	-0.234	-0.272

The exposure of these industries to competition from foreign firms, reflected in the extent to which domestic demand for these products is satisfied by imported products, further contributes towards domestic income effects while softening the effect of increased costs of production on consumer prices as the trade position for these firms deteriorates.

3.6. Effects on Households

The effects for the different household groups are reported in Tables 8 to 10. The effects of higher electricity prices on consumer welfare depend on the size and importance of electricity bills for different household groups, labor supply effects, as well as the effects on households' income.

Table 8. Effects on Labor Supply by Household

Percent Change from Baseline

	2020	2025	2030	2035	2040
Labor Supply	0.007	0.010	-0.169	-0.182	-0.194
First Quintile (lowest income)	0.003	0.005	-0.115	-0.120	-0.126
Second Quintile	0.005	0.008	-0.169	-0.180	-0.190
Third Quintile	0.007	0.010	-0.187	-0.200	-0.214
Fourth Quintile	0.007	0.011	-0.166	-0.179	-0.191
Fifth Quintile (highest income)	0.008	0.011	-0.169	-0.183	-0.197

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Table 9. Effects on Consumer Prices by Household

Percent Change from Baseline

	2020	2025	2030	2035	2040
Consumer Prices	-0.003	-0.008	0.265	0.281	0.295
First Quintile (lowest income)	-0.005	-0.012	0.380	0.394	0.410
Second Quintile	-0.004	-0.011	0.322	0.336	0.351
Third Quintile	-0.003	-0.009	0.288	0.303	0.317
Fourth Quintile	-0.003	-0.007	0.252	0.267	0.282
Fifth Quintile (highest income)	-0.002	-0.005	0.210	0.226	0.241

Table 10. Welfare Effects: Equivalent Variation by Household

Percent Change from Baseline

	2020	2025	2030	2035	2040
All Households	-0.004	-0.001	-0.133	-0.138	-0.143
First Quintile (lowest income)	0.002	0.009	-0.299	-0.308	-0.317
Second Quintile	-0.001	0.004	-0.189	-0.193	-0.198
Third Quintile	-0.003	0.000	-0.138	-0.142	-0.146
Fourth Quintile	-0.004	-0.002	-0.120	-0.125	-0.130
Fifth Quintile (highest income)	-0.006	-0.005	-0.071	-0.076	-0.081

Our simulation results show that the premature closures lead to an overall welfare loss for households of 0.14% by 2040 relative to the reference scenario. Furthermore, these effects are highly regressive as the combined effects of reduced disposable incomes increased and, in particular, consumer prices, affect more than proportionally the lowest income groups. Indeed, the lowest income group has a welfare loss of 0.32% while the highest income group has a welfare loss of just 0.08%. The factor of regressivity is very high as the loss of the lowest income group is 3.9 times larger than the higher income groups.

4. COMPARISON WITH THE EFFECTS OF AN EQUIVALENT CARBON TAX

In the previous section, we establish that the regulated closure of the two coal-fired power plants while leading to the desired environmental effects has considerable adverse macroeconomic and distributional effects. The question is whether the same environmental results could be achieved at a lower macroeconomic and distributional cost.

In this section, we compare the effects of the forced closure of the coal-operated power plants with the effects of a carbon tax that yields the same reduction in emissions. We start by establishing that a tax increasing progressively to 100 euros per ton of CO2 would lead by 2040 to the same reductions in emissions as the early closures of the coal-fired power plants. We present the comparison of the effects of both policies in Table 11.

The detrimental economic and distributional effects of achieving the desired emissions reduction with a carbon tax are substantially larger than with the regulated closures. With an equivalent carbon tax, GDP would decline by 3.24%investment by 1.64% and exports by 6.71%. In turn, employment would decline by 1.52%, prices would increase by 1.71% and private consumption would decline by 1.30%. Overall, the carbon tax would lead to a welfare loss of 2.15% for the lowest income households and of 0.95% for the highest income. For reference, the adverse output effects are about six times as large and the adverse welfare effects about nine times as large with a carbon tax.

At this stage, one could easily argue that the regulated closure was an appropriate strategy from both the macroeconomic and the distributional perspectives. The closure of coal-fired power plants, however, does not generate any additional revenues that could be used to mitigate the detrimental effects of the policy itself. In fact, with the carbon tax, we observe decrease of 14.20% in the public debt to GDP ratio by 2040 while with the forced closure we observe a 1.89% increase. While in both cases the adverse macroeconomic effects lead to a reduction in the tax base in the economy, in the case of a carbon tax, there are sizeable tax revenues generated. The fact that the tax on carbon generates additional tax revenues provides an avenue to reversing the negative macroeconomic and distributional effects of the policy.

Table 11. Comparison of Long Run Effects (2040) of Different Decarbonization Strategies

Percent Change from Baseline

	Forced Closure of Coal-Fired Power Plants	CO_2 Tax 100 euros per ton of CO_2 Without Revenue Recycling	CO_2 Tax 100 euros per ton of CO_2 With Revenue Recycling
CO_2 Emissions	-22.02	-22.52	-21.82
GDP	-0.57	-3.24	0.92
Investment	-0.12	-1.64	2.69
Exports	-0.92	-6.71	1.40
Public Debt	1.89	-14.20	-1.63
Employment	-0.19	-1.52	0.9
Consumption	-0.14	-1.30	0.43
Equivalent Variations	-0.32 to -0.08	-2.15 to -0.95	1.10 to 0.22

In Table 11, we also present the effects of this carbon tax when the revenues it generates are recycled to reduce taxation at other distortionary margins and to promote energy efficiency. Specifically, we assume that 50% of the carbon tax revenues are used to reduce the personal income tax in a progressive manner and the remaining 50% to finance general investment tax credits. In both cases, we link these reductions to activities that promote energy efficiency. Although this is somewhat arbitrary recycling strategy, it follows a clear logic: reducing the personal income tax is instrumental in mitigating the adverse distributional effects of the carbon tax, investment tax credits are important in mitigating the adverse effects of the carbon tax on the macroeconomic performance, promoting energy efficiency is a no-regrets policy.

Under these circumstances, we see that the adverse macroeconomic and distributional effects of the carbon tax would be reversed without affecting the emissions reductions more than marginally. Furthermore, a small improvement in the public debt to GDP ratio is still observed – despite the revenue neutral nature of the experiment, the improved macroeconomic conditions lead to an expanded tax base and additional tax revenues.

Naturally, the recycling strategy presented here is merely illustrative. It is not intended to be the only possible one or the best alternative. It makes the point, however, that while a carbon tax in and of itself leads to much worse macroeconomic and distributional effects than the regulated closure, it also brings with itself – unlike the regulated closures - the extra revenues that can be used to neutralize such adverse effects.

5. SUMMARY AND POLICY IMPLICATIONS

This article examines the environmental, economic, budgetary and distributional effects of the scheduled closure of the two coal-fired power plants in Portugal. Overall, closures result in an increase in electricity prices. The electric power system adjusts to the plant closures by partially replacing coal-operated generation with natural gas. Where possible, further expanding investment in renewable energy, including hydroelectric facilities, wind turbines and solar energy systems will provide for a cost-effective way to address the capacity shortfall associated with discontinuing coal-operated electricity generating units. Finally, an increase in electricity imports partially compensates the decline in domestic electric production.

The increase in electricity prices due to the early closure of the coal-operated power plants reverberates throughout the economy, leading to detrimental macroeconomic and distributional effects. The negative macroeconomic effects are widespread and notable across sectors of economic activity. The distributional effects are pronounced and highly regressive. These effects also raise concerns with respect to international competitiveness and to social justice.

It is informative to compare the results of the scheduled closures to a tax on carbon emissions with the technical capacity to reduce carbon dioxide emissions by the same amount by 2040. The negative economic and distributional effects of closing coal-fired power plants are substantially lower than a carbon tax with revenues used to finance the public debt consolidation or a lump sum transfer to households. The closure of coal-fired power plants, however, does not generate any additional revenues that can be used to mitigate the negative effects of the policy, something that an appropriately designed environmental fiscal reform can produce.

These results lead to several clear and important policy considerations. The IPCC (2018) special report has set as a goal of a 45% reduction in emissions by 2030 relative to 2010 levels. This goal has been adopted by the new roadmap for carbon neutrality in Portugal [APA (2019)]. The current reference scenario forecasts for CO2 emissions place emissions in 2030 at a level that is 12% above the 2010 levels (Belbute and Pereira, 2019). This leaves a gap of 57% of 2010 levels to be achieved by policy means. In this paper, we show that the forced closure contributes with 22% to bridge this gap, thereby still leaving the need for a policy effort leading to further reductions in emissions by 2030 equivalent to 35% of 2010 emissions levels. Accordingly, the first important policy implication of this work is that the regulated early closure of the two coal-fires power plants is an important step but by no means a sufficient one in our quest to fulfill the decarbonization goals.

In more general terms, our results suggest that in our quest for decarbonization the use of a serious and economy wide carbon tax with revenue recycling in the context of environmental fiscal reform is preferable to the rather narrow command-and-control policy approach of scheduled closure of coal-operated power plants. This alternative would allow all economic agents to endogenously adapt to the cost of carbon dioxide emissions while at the same time neutralizing the adverse economic and distributional effects. Overall, this alternative policy would allow for the same type of environmental gains with lower economic and distributional costs.

The use of a carbon taxation instead of command-and control regulation mandating the closure of coal-fired power plants presents conceptual, practical, and pedagogical advantages. From a conceptual perspective, carbon taxes provide a focused signal for households and firms with respect to the costs associated with polluting activity. In addition, that tax provides a much broader scope by targeting a broader spectrum of activities than a more concentrated industrial policy of plant closures. Indeed, a carbon tax is a focused instrument reaching a very broad spectrum of activities that produce emissions relative to the scheduled closure of coal-fired power plants. From a pragmatic perspective, the tax on carbon provides revenues needed to counteract the negative economic and distributional effects of policies that will increase the price of energy products. Form a pedagogical point of view a carbon tax makes it clear that the cause of the problem is ‘all of us’ not some remote ‘them’.

Naturally, introducing a meaningful and all-encompassing carbon tax is not a trivial matter and dealing with the issue of revenue recycling even less so. The type of policy commitment and leadership this requires may not be present. The level of political consensus it demands may not be possible. In other words, the ideal policy alternative may be a chimera. In such a situation, and when coal-fired power plants are responsible for such a large fraction of national carbon dioxide emissions, a regulated early closure may indeed be a reasonable alternative to achieve meaningful emissions reductions in a relatively short period of time.

Finally, and although this is an energy policy paper applied to the Portuguese economy and its policy implications directly relevant for the Portuguese case, its interest is far from parochial. The quest for decarbonization is universal. The use of coal-fired power plants widespread. The number of regulated early closures of such power plants growing. And, concerns over the macroeconomic and distributional effects of environmental policies unavoidable if there is some hope of meaningful policies ever being adopted.

APPENDIX

Table A1. The Dynamic General Equilibrium Model - The Model Structure

The Production Sector

$$Y_t = A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})\, AGG\_E_t^{\rho_{va}}\right)^{1/\rho_{va}} \tag{1}$$

$$VA_t = A_{va,t}(L_t^d HK_t)^{\theta_L} K_t^{\theta_K} KG_t^{1-\theta_L-\theta_K} \tag{2}$$

$$K_{p,t+1} = (1-\delta_k)K_{p,t} + I_{p,t} - \mu_k \frac{I_{p,t}^2}{K_{p,t}} \tag{3}$$

$$\begin{aligned} NCF_t = {} & Y_t - \left(1+\tau_{fssc}\right)w_t(L_t^d HK_t) - I_{p,t} - I_{W,t} - (1-\rho_I)\tau_{vat,I} I_{p,t} - p_{e,t}E_t \\ & - \tau_{cit}\left(Y_t - \left(1+\tau_{fssc}\right)w_t(L_t^d HK_t) - \alpha I_{p,t} - \alpha I_{w,t} - p_{e,t}E_t\right) + \tau_{itc,I} I_{p,t} + \tau_{itc,RI} I_{w,t} \end{aligned} \tag{4}$$

$$\alpha = [1-(1+g)^{-NDEP}]/NDEP[1-(1+g)^{-1}] \tag{5}$$

$$\theta_L \gamma_{VA} A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})AGG\_E_t^{\rho_{va}}\right)^{1/\rho_{va}-1} VA_t^{\rho_{VA}} = (1+\tau_{FSSC})w_t L_t^d HK_t \tag{6}$$

$$\frac{I_t}{K_t} = \frac{1}{2\mu_I} - \left[1 + (1-\rho_I)\tau_{VAT,I} - \alpha\tau_{CIT} - \tau_{ITC}\right](2\mu_I q_{t+1}^K)^{-1}(1+r_{t+1}) \tag{7}$$

$$q_t^K = (1-\tau_{CIT})\theta_K \frac{Y_t}{K_t} + \frac{q_{t+1}^K}{1+r_{t+1}}\left[1 - \delta_K + \mu_I\left(\frac{I_t}{K_t}\right)^2\right] \tag{8}$$

The Energy Sector

$$AGG\_E_t = A_{E,t}\left(\gamma_E\, Crude\ Oil_t^{\rho_e} + (1-\gamma_E)\, NTF_t^{\rho_e}\right)^{1/\rho_e} \tag{9}$$

$$p_{e,t}E_t = p_{fe,t}FE_t + \left(p_{crude\ oil,t} + emission\_factor_{oil}\tau_{carbon}\right) Crude\ Oil_t \tag{10}$$

$$p_{fe,t}FE_t = \sum_{i=1}^{n}\left(p_{f,i,t} + emission\_factor_f\tau_{carbon}\right)F_{i,t} \tag{11}$$

$$\left(p_{f,i,t} + emission\_factor_f\tau_{carbon}\right)\theta_{f,j}F_{i,t} - \left(p_{f,j,t} + emission\_factor_f\tau_{carbon}\right)\theta_{f,i}F_{j,t} = 0 \tag{12}$$

$$\begin{aligned} & \theta_E \frac{AGG_{E_t}}{FE_t} A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})AGG_{E_t}^{\rho_{va}}\right)^{1/\rho_{va}-1} \\ & \times (1-\gamma_E)A_{E,t}\left(\gamma_E\, Crude\ Oil_t^{\rho_e} + (1-\gamma_E)\, NTF_t^{\rho_e}\right)^{1/\rho_e-1} NTF_t^{\rho_e} - p_{fe,t} = 0 \end{aligned} \tag{13}$$

$$\begin{aligned} & \frac{AGG_{E_t}}{Crude\ Oil_t}(1-\gamma_{VA})A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})AGG_{E_t}^{\rho_{va}}\right)^{1/\rho_{va}-1}\gamma_E \\ & \times A_{E,t}\left(\gamma_E\, Crude\ Oil_t^{\rho_e} + (1-\gamma_E)\, NTF_t^{\rho_e}\right)^{1/\rho_e-1} Crude\ Oil_t^{\rho_e} - p_{crude\ oil,t} = 0 \end{aligned} \tag{14}$$

$$NTF_t = A_{E2,t}\left(\varphi_{cf}RK\right)_t^{\theta_{RK}} \prod_{i=1}^{n} F_{i,t}^{\theta_{f,i}} \tag{15}$$

$$RK_{t+1} = (1-\delta_{rk})RK_t + I_{w,t} - \mu_{rk}\frac{I_{w,t}^2}{RK_t} \tag{16}$$

$$\frac{I_{w,t}}{RK_t} = \frac{1}{2\mu_{rk}} - \left(1 + (1-\rho_I)\tau_{vat,RI} - \alpha\,\tau_{cit} - \tau_{itcr}\right)(2\mu_{rk}q_{t+1}^{RK})^{-1}(1+r_{t+1}) \tag{17}$$

$$q_t^{RK} = \frac{\partial\pi_t}{\partial RK_t} = (1-\tau_{cit})\theta_{RK}\frac{Y_t}{RK_t} + \frac{q_{t+1}^{RK}}{(1+r)}\left((1-\delta_{rk}) + \mu_{rk}\left(\frac{I_{w,t}}{RK_t}\right)^2\right) \tag{18}$$

$$CarbonEmissions_t = \sum_{f}^{N} emission\_factor_f F_{i,t} + emission\_factor_{oil} Crude\ Oil_t \tag{19}$$

Table A1. The Dynamic General Equilibrium Model - The Model Structure (con't)

The Household Sector

$$U_{a,t} = \frac{\sigma}{\sigma-1}\sum_{v=0}^{\infty}\gamma^{v}\beta^{v}\left[c_{a+v,t+v}^{\frac{\sigma-1}{\sigma}} + B\ell_{a+v,t+v}^{\frac{\sigma-1}{\sigma}}\right] \tag{20}$$

$$\sum_{v=0}^{\infty}\gamma^{v}[1+(1-\tau_r)r_{t+v}]^{-v}(1+\tau_{VAT,C})C_{a+v,t+v} = TW_{a,t} \tag{21}$$

$$TW_{a,t} \equiv HW_{a,t} + FW_{a,t} + PVF_t \tag{22}$$

$$\begin{aligned} HW_{a,t} = \sum_{m=0}^{\infty}\left(\frac{\gamma}{1+(1-\tau_r)r_{t+m}}\right)^{m}\Big((1-\tau_{pit})\big((1-\tau_{wssc})w_{t+m}(\bar{L}-\ell_{a+m,t+m})HK_{t+m} + TR_{t+m}\big) \\ + R_{t+m} - LST_{t+m}\Big) \end{aligned} \tag{23}$$

$$\begin{aligned} FW_{a,t} = {} & \big(1+(1-\tau_r)r_{t-1}^{pd}\big)PD_{t-1} + (1-\tau_\pi)NCF_{t-1} - \big(1+r_{t-1}^{fd}\big)FD_{t-1} \\ & +(1-\tau_{pit})\big((1-\tau_{wssc})w_{t-1}(\bar{L}-\ell_{a-1,t-1})HK_{t-1} + TR_{t-1}\big) + R_{t-1} - LST_{t-1} \\ & -(1+\tau_{vat})C_{a-1,t-1} \end{aligned} \tag{24}$$

$$(1+\tau_{vat})C_t = [1-(1+(1-\tau_r)r_{t-1})^{\sigma-1}\gamma\beta^{\sigma}](HW_t + (PD_t - FD_t) + PVF_t) \tag{25}$$

$$\ell_t = \left(\frac{B(1+\tau_{vat})}{(1-\tau_{wssc})(1-\tau_{pit})w_t(1-UR_t)HK_t}\right)^{\sigma} C_t \tag{26}$$

The Public Sector

$$U_{public} = \sum_{t}[(C_t\ell_t^{p_1})^{\alpha_C}CG_t^{1-\alpha_C}]\,(1+(1-\tau_r)r_t^{PD})^{-t} \tag{27}$$

$$PD_{t+1} = (1+r_t^{PD})PD_t + (1+\tau_{vat,cg})CG_t + (1+\tau_{vat,ig})IG_t + (1+\tau_{vat,ih})IH_t + TR_t - T_t \tag{28}$$

$$T_t = PIT_t + CIT_t + VAT_t + FSSC_t + WSSC_t + LST_t \tag{29}$$

$$KG_{t+1} = (1-\delta_{kg})KG_t + IG_t - \mu_{kg}\frac{IG_t^2}{KG_t} \tag{30}$$

$$HK_{t+1} = (1-\delta_{hk})HK_t + IH_t - \mu_{hk}\frac{IH_t^2}{HK_t} \tag{31}$$

$$\frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_{t+1}^{PD})} = \frac{q_t^{PD}}{(1+(1-\tau_r)r_t^{PD})} \tag{32}$$

$$q_{t+1}^{PD} = (1-\alpha_c)\left(\frac{C_t\ell^{p_1}}{CG_t}\right)^{\alpha_C}(1+(1-\tau_r)r_t^{PD}) \tag{33}$$

$$-q_{t+1}^{PD} = q_{t+1}^{kg}\left(2\mu_{kg}\frac{IG_t}{KG_t}\right) \tag{34}$$

$$\begin{aligned} q_t^{KG} = {} & \frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_t^{PD})}\left((\tau_\pi(1-\tau_{cit})+\tau_{cit})\frac{\partial Y_t}{\partial KG_t}\right) \\ & + \frac{q_{t+1}^{kg}}{(1+(1-\tau_r)r_{t+1}^{PD})}\left((1-\delta_{kg}) + \mu_{kg}\left(\frac{IG_t}{KG_t}\right)^2\right) \end{aligned} \tag{35}$$

$$-q_{t+1}^{PD} = q_{t+1}^{hk}\left(2\mu_{hk}\frac{IH_t}{HK_t}\right) \tag{36}$$

$$\begin{aligned} q_t^{HK} = {} & \frac{q_{t+1}^{PD}}{(1+(1-\tau_r)r_t^{PD})}\left((\tau_{pit}(1-\tau_{fssc}) - (1-\tau_\pi)(1+\tau_{cit})\tau_{fssc} + \tau_{wssc})\frac{\partial Y_t}{\partial HK_t}\right) \\ & + \frac{q_{t+1}^{hk}}{(1+(1-\tau_r)r_{t+1}^{PD})}\left((1-\delta_{hk}) + \mu_{hk}\left(\frac{IH_t}{HK_t}\right)^2\right) \end{aligned} \tag{37}$$

Table A1. The Dynamic General Equilibrium Model - The Model Structure (con't)

Market Equilibrium

$$(1 - UR_t)LS_t = L_t^d \tag{38}$$

$$Y_t = \sum_{i=1}^{n} p_{f,i,t}F_{i,t} + p_{crude\ oil,t}Crude\ Oil_t + C_t + I_{p,t} + I_{w,t} + CG_t + IG_t + IH_t - NX_t \tag{39}$$

$$FD_{t+1} = (1 + r_t^{fd})FD_t + NX_t - R_t \tag{40}$$

$$FW_t = PD_t - FD_t \tag{41}$$

Table A12. 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
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

Table A2. The Dynamic General Equilibrium Model - The Basic Data Set (con't)

Public sector data (% of Y_0)		
T_0	Total tax revenue	41.958
PIT_0	Personal income tax revenue	5.710
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
$2q_0^{PD}$	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
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

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
Household parameters			
		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
Emissions factor			
	$emission\_factor_{oil}$	Emissions factor for oil (tCO_2 per TJ)	72.600
	$emission\_factor_{coal}$	Emissions factor for oil (tCO_2 per TJ)	90.200
	$emission\_factor_{gas}$	Emissions factor for oil (tCO_2 per TJ)	55.800

Table A3. The Dynamic General Equilibrium Model – The Structural Parameters (con't)

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

Public sector parameters - outlays 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

Note: C indicates calibrated parameter.

Table A4. The Dynamic General Equilibrium Model - Model Variables

Variable	Description
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
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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