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On the Macroeconomic and Distributional Effects of the Scheduled Closure of Coal-Operated Power Plants in Portugal

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Abstract

This article examines the economic, budgetary, distributional and environmental impacts of the closure of coal-fired power plants using a multi-sector and multi-household dynamic general equilibrium model of the Portuguese economy. These plant closures and limits to the operation of coal generating capacity in Portugal can be expected to result in an increase in electricity prices, due to an increased reliance on electricity produced in Spain, and an increase in the use of natural gas in domestic electricity production. These price effects lead to detrimental macroeconomic effects, as well as adverse distributional effects. The closure of coal-operated power plants, however, has a significant and positive effect on the environment. We argue, however, that a carbon tax with the same environmental impact would have substantial conceptual, pragmatic and pedagogical advantages over scheduled plant closures. Primarily, it would generate tax revenues that could be used to reverse the adverse macroeconomic and distributional effects of the favorable environmental effects.

Keywords: Dynamic General Equilibrium, Coal-operated Power Plants, Energy Taxes, Macroeconomic Effects, Distributional Effects, Environmental Effects, Portugal

JEL Classification: C68, E62, H23, Q43, Q48.

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1. Introduction

In November 2017, the Portuguese Government announced its commitment to retire all coal-fired power plants by 2030. In addition, in the context of the 2018 State Budget, the Portuguese government extended the tax on energy products in Portugal (Impostos sobre Produtos Petroliferos e Energeticos, ISP hereafter) to include the taxation of coal used in electricity generation. The ISP has a fixed component of 4.26 Euros per ton of coal used. It also has an additional component, currently 6.85 Euros per ton of CO2, depending on the carbon content of the fuel, indexed to the carbon price in the European Union Emissions Trading System (EU-ETS, hereafter). This article examines the economic, budgetary, distributional, and environmental impacts of the closure of coal-fired power plants and the new ISP rules 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 Power Plant is located in Setubal and was commissioned in 1985. It has a capacity of 1192 MW and is operated by Energias de Portugal (EDP). The Pego Power Plant is located in Santarém and 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.

Coal-fired power plants play a major role in the Portuguese energy system. Thermal production of electricity from coal accounted for 21% of the electricity generated in Portugal in 2016 and 26% in 2017. Sines, the larger of the two plants, accounted for approximately 14% of electricity production in 2016 and 18% in 2017 while Pego accounted for near 7% of electricity production in 2016 and 8% in 2017 (DGEG, 2018). These power plants account for more than half of thermal production of electricity in Portugal with natural gas accounting for the remainder of thermal production. In addition, coal-fired electricity generating units are a substantial component of electric power operators generating portfolios. Finally, in 2015, 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.

Accordingly, the environmental impact of these plants is also substantial. In 2015, coal-fired power plants accounted for 17.6% of greenhouse gas (GHG) emissions in Portugal. As such, the power plants in Sines and Pego are among the largest contributors to GHG emissions in Portugal (APA, 2018).

The objective of this research is to examine the effect of the closure of these coal-fired power plants in Portugal. Specifically, we consider four research questions. First, what are the effects of closing coal-fired power plants in Portugal in 2030 in the absence of any changes in the ISP taxation? Second, what are the effects of the changes in ISP tax rules in an environment in which coal-fired power plants close as scheduled? Third, what are the effects of the changes in ISP tax rules in an environment in which operators decide to close coal-fired power plants ahead of the scheduled closure dates as a response to the increases in operation costs implied by the new ISP rules? Fourth, how are the environmental, economic, budgetary and distributional effects of closing coal-fired power plants affected by fossil fuel prices set in international markets and the price of carbon in the EU-ETS as well as by the ability of substituting domestic electricity generation by electricity imports?

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, 2017a, 2017b, 2017c) and 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). In general terms, 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 Bye et al. (2012), Goulder and Hafstead (2013), Bhattarai et al. (2016, 2017), 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 present the principal results of our analysis of the effect of closing these coal fired power plants as scheduled in 2030. Section 4 discusses the impact of the extension of the tax on energy products to coal used in electricity generation and the effects of accelerated plant closures on the economy, the public budget and on greenhouse gas emissions. Section 5, presents some sensitivity analysis results highlighting the role of imports of electricity in the identification of the effects of the scheduled closures. Section 6, compares the results in this paper with the effects of other related energy policies in Portugal. Finally, Section 7 provides a summary, policy implications, and concluding thoughts.

2. The Dynamic General Equilibrium Model and Simulation Design

What follows is necessarily a very brief and general description of the design and implementation of the new multi-sector, multi-household dynamic general equilibrium model of the Portuguese economy. More information is provided in the Appendix [see Pereira and Pereira (2017d) for further details].

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 in a dynamic general equilibrium framework. 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 their capital stock to yield optimal output, labor demand, and investment demand behaviors. 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 European Trading System 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 European Trading System 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, in turn, 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: commodity markets, factor markets, and financial 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. 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 must equal the value of domestic investment plus the budget deficit.

The evolution of the economy is described by the optimal and endogenous change in the stock variables – five household-specific financial wealth variables and thirteen sector-specific private capital stock variables, as well as their respective shadow prices/co-state variables. 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 endogenous and optimal link between subsequent time periods. Accordingly, the model can be conceptualized as a large set of nonlinear difference equations, where critical flow variables are optimally determined through optimal control rules.

The intertemporal path for the economy is described by the behavioral equations, by the equations of motion of the stock and shadow price variables, and by 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 ultimately 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.

2.4 Reference Case, Counterfactual scenarios and Simulation Design

The numerical implementation and calibration of the model is consistent with the economy being in a long-term steady state trajectory mimicking the average data for 2005-2014. The reference case for our simulations is obtained from this steady state trajectory by incorporating into it international fossil fuel price and CO_2 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.

Our reference case assumes that coal-fired power plants are operational indefinitely, and that the ISP tax rules on such activities in effect in 2017 apply for the time horizon of the model.

The counterfactual scenarios are designed around two issues: the scheduled closure of Sines and Pego in 2030, as announced by the Government on November 2017, and the changes to the ISP tax after 2018 to include coal used in the generation of electricity, which will impact the competitiveness of these assets in the short term.

There are two sets of additional ISP rules. The first is an energy component, a unit tax which consists of a fixed amount depending directly on the volume of coal used. The second is an additional component, a tax that reflects the carbon content of coal and which is indexed to the price of carbon in the EU-ETS. Specifically, the unit tax rate applying to the purchases of a ton of coal is given by:

$$\tau_{isp,fuel,t} = \tau_{unit,fuel,t} + \tau_{carbon,c,t} \times \varepsilon_{carbon,c}$$

where, $\varepsilon_{carbon,c}$ is the conversion factor between physical units of coal and its carbon content.

To account for the impacts of these measures, five counterfactual scenarios are considered:

- CF1: Discontinuing coal-fired power plants under the current closure schedule of 2030 for Sines and Pego and under no changes to the ISP rules.
- CF2: Discontinuing coal-fired power plants under the current closure schedule of 2030 for Sines and Pego and under the new ISP tax rules for energy component alone (fixed amount).
- CF3: New ISP tax rules for energy component alone (fixed amount) under a modified earlier closure schedule of 2025 for Sines and Pego, as the agents in the market react to the increased operational costs
- CF4: Discontinuing coal-fired power plants under the current closure schedule of 2030 for Sines and Pego and under the new ISP tax rules (fixed amount as well as on carbon content).
- CF5: New ISP tax rules (fixed amount as well as on carbon content) under an accelerated closure schedule of 2020 for Sines and 2021 for Pego, as the agents in the market react to the increased operational costs

The simulation results are presented as percent deviations from the model simulations in the reference scenario, thereby allowing for a direct comparison across counterfactual scenarios. In our discussion of the results, we focus mostly on the effects observed by 2040, which we will refer to as the long-term effects. Naturally, when the issue demands it we consider the transitional effects as well.

We focus on the impact of these five policy scenarios in four main domains. First, we consider the effects on the energy sector in general and the electricity market in particular, including impact on CO_2 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. They reflect equilibrium conditions and therefore a balance between supply and 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 additional considerations induced by 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. Accordingly, electricity prices in the model can be conceptualized as average production prices for the amounts of electricity produced under the prevailing market demand conditions.

3. Effects of the Scheduled Closure of Coal-Operated Power Plants in 2030

In this section, we discuss the energy, environmental, economic, and distributional effects of discontinuing coal-fired power generation in Sines and Pego. We consider the currently scheduled plant closure date of 2030 and the old ISP energy and carbon tax rules in effect prior to 2018.

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 affects the costs of production across different sectors of economic activity and expenditure patterns across different household groups.

3.1 Effects on Electricity Prices and Electricity Markets

The effects of the closure of coal-operated power plants by 2030 as intented by the Government on electricity prices and the electricity markets are reported in Tables 1 and 2.

Our simulation results suggest that the scheduled closures of Sines and Pego lead to an increase in the price of electricity of 7.1% in 2030 and 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.

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.

3.2 Effects on Final Energy Markets and CO_2 Emissions

The effects of the scheduled closures of coal-operated power plants on final energy and CO_2 emissions are reported in Tables 3 and 4. Higher electricity prices due to the closure of coal-fired electric power plants in Portugal 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.

Discontinuing the use of coal in the production of electricity in Portugal can contribute towards a very substantial reduction in carbon dioxide emissions. CO_2 emissions are 22.0% lower than in the reference scenario in 2040. Not surprisingly, the reduction in CO_2 emissions stem primarily from eliminating the use of coal in electricity generation. Emissions reductions among other industrial sectors of economic activity, particularly those not participating in the European Union Emissions Trading System (ETS), 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 CO_2 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.

3.3 On the Macroeconomic Effects

The macroeconomic effects of the scheduled closures of coal-operated power plants 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.

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.

3.4 Industry Effects

The industry effects of the scheduled closures of coal-operated power plants are reported in Tables 6 to 9. The adverse aggregate effects of the scheduled closures on GDP reflects reductions in production activity across the board. With small quantitative differences, the same patterns of results can be observed for employment changes across sectors of economic activity.

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 services are marginal.

In turn, the very small sector of biomass is the only one 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 of the scheduled closure of coal plants by 2030 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 exports and of the foreign account position induced by the scheduled closure of the coal-operated power plants, as discussed above.

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.

3.5 Effects on Households

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.

The effects of the scheduled closures of coal-operated power plants by the Government by 2030 for the different household groups are reported in Tables 10 to 12. 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 in 3.9 times larger than the higher income groups.

4. On the Effects of the 2018 Extension of the ISP to Coal in Electric Power

In this section, we analyze the effects of the 2018 extension of the ISP tax to coal used in electricity generation for the interim period until their scheduled closure. As mentioned above, there are two sets of additional ISP rules. The first is an energy component, which consists of a fixed amount depending directly on the volume of coal used. The second is an additional component that reflects the carbon content of coal and which is indexed to the price of carbon in the EU-ETS.

We consider first a set of scenarios, CF2 and CF3, in which the extension to the ISP includes only the fixed unit tax on energy, and then a second set of scenarios, CF4 and CF5, in which both the energy and carbon tax components are in place.

The effect of the additional tax burden will depend on how long the coal-operated power plants will remain active. At the same time, the increase in fuel costs for electric power facilities associated with the expanded ISP tax is expected to move up the effective closure dates for the two power plants as a result of operational considerations. The policy, as designed, will make the plants unprofitable and lead to their closure years earlier than the date determined by the functional life expectancy of the plant. In this case, operators in the electric power industry will react to the additional tax burden with an accelerated closure schedule.

Accordingly, we consider throughout two alternative situations. The first, CF2 and CF4, in which there is no reaction by operators in the electric power industry and the plant closure remains as scheduled for 2030. A second, CF3 and CF5, in which the industry responds to the additional tax burden by closing the coal-operated power plants ahead of the scheduled schedule. Specifically, we consider that the increase in fuel costs associated with the energy component of the tax moves up the plant closure by 5 years (from 2030 to 2025). In addition, the increase in fuel costs driven by both the base fixed energy tax and the carbon content of the fuel are large enough to justify the closure of these plants nearly 10 years earlier than expected based on operational considerations.

4.1 On the Long-Term Effects of the Different Closure Schedules

The long-term effects of the scheduled closures of coal-operated power plants under the new ISP rules are reported in Tables 13 to 16 and Figures 1 to 4. While the coal-operated power plants remain active, the higher costs associated with the production of electricity from coal due to the increase in the ISP tax burden will increase the cost of generating electricity relative to the status quo. Naturally, such price effects disappear in the long term as both power plants eventually close.

Accordingly, the main differences among the five scenarios, the CF2 to CF4 with the new ISP rules, and the central counterfactual scenario, CF1, with the old ISP rules, are going to be short-term transitional effects. We would not expect significant differences in the long-run trajectories for the flow variables. The same is not true, naturally, for the stock variables, such as public and foreign deficits or accumulated reduction in emissions.

Our simulations results conform to this intuition. Indeed, the differences in the long-term energy, environmental, macroeconomic, and distributional effects are marginal. All of the significant differences in the effects of these policies among the different scenarios occur in the 2020s and depend strictly on how long the power plants remain in activity. Accordingly, we focus in the differences in the transitional effects.

4.2 On the Effects of the 2018 ISP Extension to the Energy Tax

It is informative to compare the transitional effects associated with the 2018 extension to the ISP tax on energy products under the scheduled Government 2030 closure date, CF2, and with an accelerated plant closure, CF3, to our central counterfactual scenario, CF1, with the same Government intended 2030 closure date and the old ISP rules. The detailed simulation results are presented in Tables 17 to 24 and Figures 5 to 19 while the cumulative effects are summarized in Table 25.

We see a short-run and temporary increase in the price of electricity that ripples throughout the economy. Ultimately, economic conditions are weaker than in the central counterfactual scenario, CF1, in terms of GDP, employment, and foreign debt. Should the coal-operated power plants remain operational through 2030 we would observe a marginal improvement in the public sector account, reflected in lower levels of public indebtedness, due to the additional tax revenues. Finally, the regressive distributional effects on household welfare are exacerbated by the additional costs of generating electricity.

These transitional effects are rather small and effectively insignificant in the instances in which the plants in Sines and Pego remain operational through 2030 in scenarios CF1 and CF2. They translate into small cumulative changes in greenhouse gas emissions and in economic performance, measure by the accumulated losses to GDP and to employment. The public debt position, however, improves by 4.4%; and the cumulative welfare losses deteriorate a further 1.3% in the CF2 scenario relative to the CF1 scenario, reflecting the additional tax burden.

The accelerated plant closure by 2025 induced by the additional operating costs, as in CF3, yields more substantial differences relative to the central counterfactual scenario, CF1. With the earlier closure, we observe an additional cumulative reduction in CO_2 emissions of 42.1%. These additional reductions in emissions reflect the additional five years during which the coal-operated power plants will be inactive and not contributing towards atmospheric emissions.

The accelerated closures also move forward the reduction in economic activity and weaker economic conditions associated with higher electricity costs. The cumulative effect of these additional years of weaker economic conditions is that the cumulative indicators of economic performance deteriorate, accumulated GDP losses increase by 45.4% and accumulated employment-years increase by 47.5% vis-à-vis CF1. Noticeably, the intertemporal welfare indicator are 32.0% lower than in the central case CF1.

Importantly, in CF3, public debt now deteriorates by 124.5% relative to the central CF1 case. The larger increase in public debt is due to the combined effect of first, the fact that addition tax revenues from the extension to the tax on energy products applies for a shorter period of time due to the accelerated plant closures and second, that the negative contractionary effects last longer with an accelerated closure schedule.

4.3 On the Effects of the 2018 ISP Energy and Carbon Tax Extensions

Finally, we consider the effects of the additional costs associated with both the energy and the carbon tax component of the extension to the ISP tax. Again, the detailed simulation results are presented in Tables 17 to 24 and Figures 5 to 19 while the cumulative effects are summarized in Table 25. In both CF4 and CF5, electric power producers face the additional tax on the energy content as well as the indexed tax on carbon in the cost of coal used in the production of electricity. In these cases, the patterns of the results are similar to the cases in the previous subsection that considers only the new rules on the energy component of the ISP. The differences in the cumulative environmental, macroeconomic, and distributional effects, however, are substantially more pronounced.

Under the scheduled closures, CF4, the new ISP rules applying to both energy and carbon content have relatively small effects. There is a marginal reduction in emissions, which goes hand in hand with small deteriorations in economic performance and household welfare relative to central counterfactual scenario, CF1. The effects on the public sector account are more favorable with the extension to the tax on energy products only under the assumption that the plants remain operational through 2030. In this case, we would observe a 9.3% gain in the public debt position in CF4 with respect to CF1.

The situation is fundamentally different if plant operators accelerate the closure schedule due to operational considerations and the plants cease operation in 2020. It is important to note that these changes are due exclusively to the early closure itself as the extensions to the ISP tax barely becoming effective before seeing the closure of these two facilities. The accumulated gain in CO_2 emissions reductions relative to CF1 increase by 82.2%, which reflects the additional decade without coal-operated power plants.

In turn, the negative effects on economic performance also occur concomitantly for an additional decade. The accumulated detrimental effects on GDP increase by 89.4% and the accumulated loss in employment-years increases by 95.1% relative to the central counterfactual scenario in CF1. The intertemporal effects on household welfare increase by 61.3%. The effects on public debt are quite severe under CF5, showing an 310.3% increase in the public debt in CF5 relative to CF1, as the early closure substantially decreases the tax bases as it deepens the contractionary effects and eliminates the tax revenues benefits of the changes to the ISP.

5. Sensitivity Analysis

In this section, we consider the sensitivity of our results to several key elements of our reference scenario. Because of its importance to our discussion, we focus on our central counterfactual scenario, CF1, where the coal-operated power plants close in 2030 and the ISP rules in effect in 2017 continue indefinitely.

5.1 Sensitivity Analysis: international fossil fuels and carbon prices

We consider first the sensitivity analysis with respect to the two most fundamental pieces of information used to derive the reference scenario, specifically the projections of the international fossil fuel prices and of the carbon prices in the EU-ETS markets. We consider a lower price and a high price scenario for fossil fuel prices and carbon prices. As with the values used for the reference scenario and the different counterfactual simulations, these scenarios are based on the information in the World Energy Outlook by the International Energy Agency for the fossil fuel prices, and the Bloomberg News Energy Finance for carbon prices.

Each of these values reflects international market forces. The two alternatives, the low price and high price scenarios, are asymmetric around the central scenario due to the potential likely upside and downside risk in each case. Our high price scenario is much closer to the central scenario than is the low price scenario.

In all cases, we modify the reference scenario to consider these alternative international price projections. Accordingly, differences in the results across the low and high scenario can be interpreted as differences in the effects of the Government's intended 2030 closure dates under different international market environments. The low prices scenario provides a weaker market incentive for decarbonization relative to the central assumptions, and a more substantial reduction in natural gas prices relative to coal prices. In contrast, the high prices scenario provides for a much greater market incentive for decarbonization and considers a much higher price for natural gas relative to coal. Both of these considerations affect individual decisions on energy consumption and the potential increase in electricity prices due to the increased use of natural gas to replace coal generation.

Sensitivity analysis results are presented in Tables 26 to 29 and Figures 20 to 23. While the alternative price scenarios do not introduce substantial qualitative differences in the effects of the scheduled plant closures, an interesting pattern of results does emerge. Under the low price scenario, with a lower inherent market pressure for decarbonization, the effects of the power plant closures on electricity prices and domestic electricity generation are more pronounced. The same is true for foreign production reflected in the increased reliance on imported electricity under these more favorable international market conditions. These two factors translate into smaller changes in electricity demand as well as final energy demand. Accordingly, the environmental gains are substantially smaller under the low price scenario.

In turn, greater increase in electricity prices in the low price scenario and its subsequent impact on production costs produces larger macroeconomic costs associated with the scheduled closures in terms of GDP, employment, and foreign debt, relative to the central scenario. Finally, although the patterns of the distributional effects in each case reflects a regressive component to the policy, the welfare losses are smaller, in absolute value, in an environment of lower fossil fuel and carbon prices, reflective of smaller reductions in private consumptions led by smaller reductions in energy demand by households.

5.2 Sensitivity Analysis: Elasticity of Substitution of Electricity Imports

The discussion in the previous subsection makes clear that the interconnectivity of the Iberian electricity market and the role of cross-border electricity imports is pivotal in the understanding both the effects of the policy but also the role that international market conditions play in the analysis. This suggests a more detailed inquiry into the role played by the elasticity of substitution between domestic electricity production and electricity imports. We consider here a less open and more open scenario, a case of with a low elasticity, which suggests the existence of substantial technological, regional congestion or other barriers to cross-border trade and a high elasticity case, which suggests the opposite. Specifically, the Armington elasticity of substitution between electricity imports and domestic electricity production, which is 4.0 in the central scenario, is 1.5 in the low case scenario and 5.5 in the high case scenario.

Sensitivity analysis results are presented in Tables 30 to 33 and Figures 24 to 27. The sensitivity analysis results fully corroborate the key role of this elasticity of substitution of electricity imports in the evaluation of the effects of the scheduled closures. A lower ability to import electricity, translates into a smaller reduction in domestic electricity production and a greater reduction in final energy demand. Accordingly, the macroeconomic effects are mitigated with the smaller contractionary supply side effects. In turn, the welfare effects are amplified with the larger contractionary demand side effects.

6. Comparisons with the Effects of Other Recent Policies

In this section, we compare the results about the effects of the forced closure of the coal-operated power plants presented in this research with the results in two other recent and related pieces of research on energy policy issues in Portugal. Because of the centrality of this scenario, we focus our comparisons on the effects under CF1, our central case, under which both Sines and Pego close in 2030 and under which the ISP tax rules prevailing in 2017 were to continue indefinitely. Comparative results are presented in Table 35.

6.1 Comparison with a Carbon Tax to achieve a 65% Reduction in CO_2 Emissions

We consider, first, the results in Pereira and Pereira (2017). This paper analyzed the environmental, macroeconomic and distributional effects of carbon taxation in Portugal consistent with achieving a reduction of 65% in emissions compared to 1990. The carbon tax required from an engineering perspective based on the shadow price for the carbon constraint and the marginal costs of control [see Seixas et al. (2017)], progressively increases to 49 and 183 Euros per ton of CO_2 by 2040 and 2050, respectively.

Given the progressive nature of the tax, increasing over time, the environmental effects of the two policies by 2040 are comparable. The detrimental economic, budgetary, and distributional effects of closing coal-fired power plants are substantially lower than the carbon tax – about ten times smaller. 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. 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.

6.2 Comparison with the Increase in the VAT Tax Rate on Electricity

We consider also the results in Pereira and Pereira (2018). This paper analyses the environmental, macroeconomic and distributional effects of the change of the VAT tax rate on electricity from 6% to 23% in Portugal.

Both the scheduled closure of the coal-operated power plants and the increase in the VAT tax rate on electricity, increase the price of electricity for households and for firms. The increase in the

VAT tax rate on electricity has negligible environmental effects. The order of magnitude of the adverse economic and distributional effects are comparable to the corresponding effects of closing coal-fired power plants. Naturally, it increases tax revenues, its main objective. In contrast, the closure of the coal-fired power plants has more substantial environmental benefits.

7. Summary and Policy Implications

This article examines the environmental, economic, budgetary and distributional effects of the scheduled closure of coal-fired power plants in Portugal. We do so in the context of a novel disaggregated dynamic general equilibrium model of the Portuguese economy that features a detailed modelling of the public sector and the energy sector.

Specifically, we consider four research questions. First, what are the effects of closing coal-fired power plants in Portugal in 2030 in the absence of any changes in the ISP taxation? Second, what are the effects of the changes in ISP tax rules in an environment in which coal-fired power plants close as scheduled? Third, what are the effects of the changes in ISP tax rules in an environment in which operators decide to close coal-fired power plants ahead of the scheduled closure dates? Fourth, how are the environmental, economic, budgetary and distributional effects of closing coal-fired power plants affected by fossil fuel prices set in international markets and the price of carbon in the EU-ETS as well as by the ability of substituting domestic electricity generation by electricity imports?

7.1 Summary of the Results

Overall, closures and limits to the coal generating capacity in Portugal 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 closure of the coal-operated power plants has a significant and positive effect on the environmental performance. At the same time, this effect is very narrow in scope, as it comes exclusively, and by design, from the electric power system. These reductions do not reflect an overall change in the patterns of energy use in the economy. This leads to a residual concern on the pedagogical value of this measure of early closure vis-à-vis system wide measures aiming at reducing emissions across the board in the country.

The increase in electricity prices due to the early closure of the coal-operated power plants reverberates throughout the economy, leading to detrimental macroeconomic effects, as well as adverse 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.

The extension of the tax on energy products to coal used in the generation of electricity provides little to no additional environmental gains, as long as private sector agents do not react to the changing profitability of these facilities and maintain the scheduled closure dates at 2030. The economic and distributional effects, however, are marginally worse than the old energy tax rules due to a small increase in production costs, and its effect on electricity prices. Naturally, there is a small gain in the public debt position.

An important result that emerges from the analysis of the effect of the expansion of the tax on energy products to coal used in electricity generation is that the effect that this may have on the profitability of coal-fired power plants, and the potential for their accelerated closure, is the determinant factor in understanding the impact of this policy. Indeed, if operators in the electric power industry react to the new ISP rules by accelerating the closure of the coal operated power plants, the situation changes substantially. The environmental gains are much more pronounced but so too are the negative economic and distributional effects. More importantly from the perspective of the public sector, the public debt position clear deteriorates due to contracting tax bases in the face of weaker economic conditions.

The five policy scenarios we consider have similar long-term effects. Over time, once the plants have closed, the extension to the tax on energy products to these facilities has no effect as the new ISP rules disappear when the power plants are effectively closed. The differences in short term transitional effects, however, are very significant, as the new ISP rules are relevant while the plants are operational, and an accelerated closures' schedule extends the duration of the adverse effects on economic performance and household welfare. The least detrimental of the five policy scenarios we consider, from both economic and social justice perspectives – when considering both the transitional and accumulated long-term effects of the policies – is the basic central scenario of scheduled closures in 2030 without changes in the ISP.

Sensitivity analysis suggests that the impact of these plant closures depends, in part, on international fossil fuel prices, as well as carbon prices in the EU-ETS. The relevance of the international market conditions in determining the effects of the scheduled closures is quantitatively marginal. Yet, scheduled closures in an environment of lower market pressure to decarbonize induce greater effects in domestic electricity generation but lower effects in terms of final electricity demand, final energy demand, and lower CO_2 emission reductions. In turn, while the macroeconomic effects are larger due to the larger effect on energy prices and energy costs, the welfare effects of the policy are smaller due to smaller reductions in private consumption led to lower reduction in final energy demand. A large increase in electricity imports plays a pivotal role.

We identify the same type of effects when considering the lower and higher elasticities of substitution of electricity imports, a proxy for how easy it is to substitute imports of electricity for domestic production. As such, a decisive factor in understanding the effects of the closure of coal fired power plants in Portugal are regulatory and market considerations in Spain. To the extent that Portugal alone shuts down its coal fired electric power plants, electricity produced from coal-fired power plants in Spain along the border with Portugal can serve to satisfy domestic demand and minimize the influence of these plants' closures in Portugal.

Finally, it is informative to compare the results of the scheduled closures to the effects of other significant policies affecting the electricity sector. The environmental effects by 2040 of closing the two power plants and introducing a tax on carbon emissions with the technical capacity to reduce carbon dioxide emissions by 65% relative to 1990 levels by 2050 are comparable. The negative economic, budgetary, 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 policies can also be compared to the effects of the increase of VAT tax rate on electricity, as both policies increase electricity prices. The scheduled closure of coal-operated power plants produces large environmental benefits while the increase in VAT tax rate has negligible environmental effects. The order of magnitude of the adverse economic and distributional effects of the two policies are comparable. Naturally, the increase in VAT increases tax revenues, its main objective, while the scheduled closure does not.

7.2 Policy Implications

These results lead to several clear and important policy recommendations. The first policy recommendation is that instead of the rather narrow command-and-control policy approach of scheduled closure of coal-operated power plants, we would recommend the use of a serious and economy wide carbon tax with revenue recycling in the context of environmental fiscal reform. 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'.

The second policy recommendation is to eliminate the new ISP rules. Regardless of whether or not the scheduled closures are enforced, there are no environmental advantages from the new ISP rules although they will certainly produce economic and distributional costs. Emissions reductions would only results from the accelerated closures of the coal generating units, in which case the adverse macroeconomic, distributional, and budgetary effects would be substantially larger.

Indeed, in 2016, Portugal introduced a tax on carbon dioxide emissions from fossil fuel combustion activities. This tax was implemented as an additional component to the existing unit tax on energy products, ISP, based on the carbon content of each type of fossil fuel with a level indexed to the EU-ETS. The tax expanded the scope of policy efforts to reduce emissions beyond the large energy-intensive industrial emitters participating in the EU-ETS to include the many households and businesses that together can make a substantial contribution towards domestic emissions reductions efforts. The additional component to the ISP for coal based on the carbon content of the fuel effectively doubles the price on carbon in electricity generation from coal and it raises both legal and equity concerns.

In contrast, the changes to the ISP based on the energy content of coal, rather than its carbon content, align the tax treatment of coal with that of other fossil fuels and is justifiable on equity grounds. It is well understood from an environmental perspective the importance of eliminating exemptions in ISP or other tax margins, such as the exemptions to the energy component of the ISP. These exemptions should be eliminated as they are detrimental for the environmental performance. They should, however, be eliminated in a methodical and comprehensive manner.

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APPENDIX

DGEP Model Description and Implementation

1. Model Description

Household Behavior

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 all household-specific, as are consumption demands, savings, and labor supply.

Household h chooses consumption and leisure streams that maximize intertemporal utility, subject to the consolidated budget constraint. The objective function is lifetime expected utility, subjectively discounted at the rate of β. Preferences, are additively separable in consumption and leisure, and take on the CES form, where σ is the constant elasticity of substitution.

C_h denotes the total consumption by household *h*, including both expenditure on goods and services. P_h is a household-specific price index which reflects consumption levels of individual goods and services as well as their prices. The household-specific price index reflects the individual basket of goods and services that each household selects. The amount of time the household spends in leisure and recreational activities is denoted by ℓ_h.

The budget constraint reflects the fact that consumption is subject to a value-added tax rate of $\tau_{VAT,C}$ and states that the households' expenditure stream discounted at the after-tax market real interest rate, $1 + (1 - \tau_r)r_{t+v}$, cannot exceed total wealth at t, $TW_{h,t}$. For the household h, total wealth, $TW_{h,t}$, is composed of human wealth, $HW_{h,t}$, and net financial wealth, $A_{h,t}$.

The household's wage income is determined by its endogenous decision of how much labor to supply, $LS_t = \bar{L} - \ell_t$, out of a total time endowment of $\bar{L}$, and by the stock of knowledge or human capital, HK_t. Labor earnings are discounted at a higher rate reflecting the probability of survival.

The effective wage rate, wHK_h, accomodates differences in income levels for the same number of work hours, by accounting for differences in worker productivity reflected in differences in the level of human capital each household has accumulated. The level of human capital for each household reflects differences in education and experience among the various household groups. In this version of the model the household-specific HK is fixed or exogenously given.

A household's labor income is augmented by international transfers, R_t, and public transfers, TR_t as well as capital income - interest payments received on public debt, PD_t, net of payments made on foreign debt, and profits distributed by corporations, NCF_t, where s_{ht} is the share of household *h* of the aggregate market portfolio.

On the spending side, taxes are paid and consumption expenditures are made. Income, net of spending, adds to net financial wealth in the form of savings. To allocate aggregate consumption to specific commodities, goods and services, consumers maximize utility from consumption subject to their budget constraint:

$$\max_{\mathbf{QH_h}} \left[\; U^h(\mathbf{QH_h}) \;\middle|\; PC_hQC_h \;\geq\; (\mathbf{1} + \boldsymbol{\tau}_{\mathbf{vat}})(\mathbf{PQ} + \boldsymbol{\tau}_{\mathbf{unit}}) \times \mathbf{QH_h}\right]$$

where $\boldsymbol{PQ}$ and $\boldsymbol{QH_h}$ denote a vector of price ($/unit) and quantity (physical units) of a good consumed over the course of a year, respectively. $PC_{ht}QC_{ht}$ represents total expenditure on goods and services by the household h at time t. Expenditure on goods and services is subject to product and service-specific value-added tax rates, $\tau_{\text{vat,c}}$, and other unit taxes, $\tau_{\text{unit,c}}$, including the tax on petroleum and energy products (ISP). At optimality, the marginal rate of substitution is equal to the market opportunity cost. The exchange rate for the individual household required to maintain a given level of utility is exactly equal to the rate at which the household can exchange these goods in the marketplace.

This general framework is applied at two different levels. First, it is applied to determine the optimal allocation of total consumption spending among the three main category of goods: transportation services, residential energy, other goods and services. Second, it is applied to determine the optimal allocation within more specific categories within each one of these three main groups.

Producer Behavior

We consider thirteen production sectors. 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.

Firms maximize the present value of the firm which serves as a source of financial wealth for households. The firm maximizes the present value Hamiltonian which reflects the firm's net cash flow and is subject to the equation of motion for private capital, and renewable energy capital, specified for hydroelectric, wind and solar power infrastructures.

The firms' net cash flow, NCF, represents the after-tax position when revenues from sales are netted of wage payments spending in energy and materials and investment spending. The after-tax net revenues reflect the presence of a private investment tax credit at an effective rate of τ_{ITC}, taxes on corporate profits at a rate of τ_{CIT}, and Social Security contributions paid by the firms on gross salaries, $w_t L_t^d$, at an effective rate of τ_{FSSC}.

The corporate income tax base is calculated as revenues net of total labor costs, $(1 + \tau_{FSSC}) w_t L_t^d$, as well as spending in energy and materials and is net of fiscal depreciation allowances over past and present capital investments, αI_t.

Output is produced using capital, labor, energy and material inputs. The production technology describes the level of output possible for the use of inputs to production employed by the firm. The production technology is assumed to be continuous and twice differentiable and thus, by the appropriate choices for the elasticity of substitution in production yields a smooth, continuous approximation to the discrete choice of processes, activities and equipment made at the plant level.

Capital, labor and energy inputs are separable into two broader categories, value added and energy inputs. Value added includes capital and labor inputs to production. A Constant Elasticity of Substitution technology is used to describe the level of value added produced from capital and labor inputs. Energy inputs consist of coal, natural gas, crude oil, refined oil products and electricity. These are aggregated according to a constant elasticity of substitution technology. The conditional demand for these inputs is defined from efforts by the firm to minimize the costs of producing the composite quantity required at the higher levels for the nested production structure.

Material inputs are goods and services produced by other industries needed in production. These material inputs are used in fixed proportions to the level of output. The firm cannot substitute among materials in production. The firm may, however, through its organization of assembly and manufacturing operations, substitute between material inputs and capital, labor and energy in production according to a constant elasticity of substitution production technology.

Private capital accumulation is characterized by the equation of motion for capital where physical capital depreciates at a rate δ_K. Gross investment, I_t, is dynamic in nature with its optimal trajectory induced by the presence of adjustment costs. These costs are modeled as internal to the firm - a loss in capital accumulation due to learning and installation costs - and are meant to reflect rigidities in the accumulation of capital towards its optimal level. Adjustment costs are assumed to be non-negative, monotonically increasing, and strictly convex. In particular, we assume adjustment costs to be quadratic in investment per unit of installed capital.

Optimal production behavior consists in choosing the levels of output supply, labor demand, aggregate energy demand, aggregate demand for intermediate materials, and demand for investment that maximize the present value of the firms' net cash flows, subject to the equation of motion for private capital accumulation.

Finally, with regard to the financial link of the firm with the rest of the economy, we assume that at the end of each operating period the net cash flow netted of investment spending is transferred to the consumers as return on their ownership of the firms.

Investment Supply and Demand

The output of various industries is used in the production of capital goods used by firms. Construction, equipment manufacturing, primary metals and other goods and services are used in the production of plant and equipment for firms. These industry determine the supply of investment goods. The supply of the investment good is a CES composite of the different types of investment goods available in the economy. Demand for individual component of the investment good is determined by the minimization of the cost of producing the desired amount of the investment good in the economy at time t. In turn, the demand for investment by firms is determined by the firms' maximization problem described above.

Financing for investment is available from savings by private households and foreign transfers reflected in the current accounts deficit and is affected by public deficits whereby reductions in tax revenues or unfinanced increases in expenditures increase the public deficit and crowd out private investment.

The Foreign Sector

The current account deficit reflects the balance of payments with the foreign sector and incorporates both the trade balance and financial flows from abroad. Because of the nature of the currency markets where the economy finds itself, we assume that the foreign exchange rate is exogenous and fixed. This means that in the absence of import and export duties, the import and export prices for the same commodity would be the same.

Net imports are financed through foreign transfers and foreign borrowing. Foreign transfers grow at an exogenous rate. The domestic economy is assumed to be a small, open economy. This means that it can obtain the desired level of foreign financing at a rate which is determined in the international financial markets. This is the prevailing rate for all domestic agents.

Domestic production and imports are absorbed by domestic expenditure and exports. Domestic demand is satisfied by domestic production and imports from abroad following an Armington specification. Goods produced domestically are supplied to both the national (domestic) market and exported internationally and follow a Constant Elasticity of Transformation (CET) specification

The Public Sector

The equation of motion for public debt reflects the fact that the excess of government expenditures over tax revenues, i.e., the public deficit, has to be financed by increases in public debt. Given the nature of our approach, the evolution of public debt is determined by the endogenous evolution of the tax revenues or more specifically by the endogenous evolution of the different tax bases. Specifically, no behavioral changes on the expenditure side are considered.

Tax revenues include personal income taxes, corporate income taxes, value added taxes as well as other product-specific taxes, social security taxes levied on firms and workers, as well as duties levied on imports and/or exports. All of these taxes are levied on endogenously defined tax bases. Residual taxes are modeled as lump sum, obtained by calibration and are assumed to grow at an exogenous rate.

On the expenditure side, the public sector engages in public consumption and public investment activities. In addition, the public sector transfers funds to households - in the form of pensions, unemployment subsidies, and social transfers also at an exogenous growth rate. Because these expenditures consistent primarily of expenditures on compensation of public sector employees and on social transfers, these expenditures are assumed to grow at an exogenous rate g. Finally, the public sector pays interest on outstanding debt

The allocation of public consumption spending among the different goods and services in the economy is responsive to relative prices and is obtained through the solution to the public sector's cost minimization problem of achieving the desired aggregate consumption level. While aggregate consumption in volume is determined exogenously, public consumption expenditure is affected by endogenous changes in prices determined by the model supply and demand considerations.

2. Data

General Data Sources

Data are from Statistics Portugal (www.ine.pt). The data are based on the Portuguese National Accounts (ESA 2010, base 2011). These data include A – main aggregates for the Portuguese economy, including 1) Gross Domestic Product and its components, 2) Income, Saving and Net Lending/ Borrowing, 3) External Balances, 4) Employment and 5) Goods and Services account. These further include B – Institutional Sectors including, the Government, Households and the Rest of the World (the Foreign Sector). We further consider specific tables by industries including Gross Value Added – Compensation of Employees, Gross Operating Surplus and Taxes/Subsidies on Production, as well as Production and Intermediate Consumption by the A38 classification of economic activity described below. We further use detailed supply and use tables to construct the social accounting matrix for Portugal.

Data for household expenditure are taken from two surveys. The first is the Inquérito ao Consumo de Energia no Sector Doméstico, a one-time survey conducted in 2010. The second is the Inquérito às Despesas das Famílias, a survey conducted every five years. The model largely employs data from the 2010/2011 survey in allocating income to household by income group and describing the expenditure patterns for each household type.

The Energy Sector

Portugal imports fossil fuels and has a large potential for renewable energy resources, namely wind, solar and hydropower. Renewable energy resources accounted for 25.9% of domestic primary energy consumption in Portugal in 2014, primarily used in the production of electricity. Petroleum and petroleum products accounted for 43.4% of primary energy consumption in Portugal in 2014. Natural gas (16.7% and coal (12.8%) are important sources of energy as well.

Transportation demand for energy amounted to 36.3% of the total final demand for energy in 2014, followed closely by industry (31.2%). Diesel is the dominant fuel in transportation in Portugal (4.072 Mtep in 2014), followed by gasoline (1.136). Residential demand for energy amounted to 16.8% of the total and demand in services accounted for 12.8%. The remaining 2.8% constitutes final energy demand in agriculture. With respect to electricity, services (36.7%) and industry (34.5%) are much more important as is residential demand for electricity (26.4% of the total). Agriculture (1.8%) and transportation (0.7%) do not use electricity extensively.

Renewable energies have made substantial advances in Portugal since 2005. In 2005, thermal electricity general amounted to 85% of the total and renewable energies, including hydroelectric, wind, geothermal and solar power, amounted to 15% of electricity generation. By 2014, electricity generation grew to account for 56.4% of electricity generated in continental Portugal lead by a substantial increase in wind energy generation that accounted for 23.4% of electricity production in 2014, a year with very favorable hydrological conditions that allowed for electricity from hydroelectric facilities to account for 31.9% of total electricity produced. The increased reliance on domestic, renewable energy sources has contributed towards a reduction in emissions factor for the electric power industry from 462 tCO_2 per Gwh in 2005 to 217 tCO_2 per Gwh in 2014.

In 2008 and 2009 the final demand for electricity in Portugal fell 1.2% and 0.9%, respectively. During the crisis that followed, electricity demand fell 8.8%, from 48.9 Twh in 2010 to 44.6 Twh in 2014, falling 3.0% in 2011 and 4.1% in 2012, respectively. This reduction in emissions is likely attributable to low levels of economic output and consumer confidence during the crisis (Eurostat, 2017)

Energy products in Portugal are subject to value added taxation and product specific taxes. Since January 1, 2011 the value added tax (IVA) rate on energy products is 23% (Lei nº51-A/2011, de 30 de Setembro), up from 19% in 2005. Energy products are subject to a specific tax on petroleum products (ISP) and to carbon taxation. Industrial use of natural gas is exempt from carbon taxation. The carbon tax rate for 2017 is based on an average price in the EU-ETS of 6.85 Euro/tCO_2 (Portaria nº 10/2017, de 09/01).

The Portuguese Economy

The Portuguese economy was dramatically affected by the sovereign debt crisis experienced in many parts of Europe since 2011. The late 1990s was a period of substantial growth in Portugal during which time the Portuguese economy grew at an average annual rate of 4.2%. During the early 2000s, the Portuguese economy began to stagnate and grew at an average annual rate of 1.5% between 2000 and 2004. Since 2005, growth in Portugal has been very weak. The real annual rate of growth of economic activity between 2005 and 2014 was -0.2%. In fact, since the financial crisis Portugal lost 6.8% of its national income between 2010 and 2013. Growth has picked up over that the last few years with the real growth rate of estimated for 2015 at 1.6%.

Gross domestic product consists of private consumption (66.44%), public consumption (19.94%), investment (19.66%) and net exports (-8.21), the difference between exports (28.75%) and imports (36.96%). From the income side, employment made up 46.23% of GDP between 2005 and 2014 while gross operating surplus for firms amounted to 41.44% of GDP. These figures imply that labor income made up 52.73% of income and capital income accounted for 47.27% of income.

Industry Data

Data are from the *Portuguese Institute for Statistics, National Accounts (Instituto Nacional de Estatistica, Contas Nacionais)*, tables C.5.2.1 – C.5.2.5 which gives the use of commodities by industry and for final demand between 2010 and 2014.

By output, the largest sectors of economic activity in Portugal are the manufacture of food products, followed by real estate services, petroleum refining, manufacture of motor vehicles, electric power, health, manufacture of chemical and chemical products, building construction, food and beverage serving services, education and products of agriculture. These sectors account for nearly half of all economic activity in the country.

The largest sectors of economic activity, in terms of employment levels between 2005 and 2014, were Wholesale and retail trade (15.6%), construction (9.3%), agriculture (7.5%), the public sector, accommodation and food services (5.8%), and manufacturing of textiles, wearing apparel and leather products (4.9%).

The principal exports in Portugal are automobiles and transportation equipment with exports from the manufacturing of transport equipment accounting for 3.2% of GDP followed by the manufacturing of textiles, wearing apparel and leather products which exported products valued at 3.1% of GDP between 2005 and 2014. Other energy intensive manufacturing industries, including basic metals and fabricated metal products (2.3%), non-metallic mineral products (2.0%) and wood and paper products (1.8%), have also been very important tradable sectors in the Portuguese economy. (Source: Statistics Portugal)

The principal products that Portugal exports are vehicle parts, refined petroleum products, leather footwear and paper. It follows then that the largest volume of exports by sector of economic activity are in the manufacture of motor vehicles (3.1 % of GDP), refined petroleum products (2.0% of GDP), the manufacture of food products, chemicals, apparel, fabricated metal products, rubber and plastics, electrical equipment and paper products. These industries account for more than half of all exports by value from Portugal between 2010 and 2014 and nearly 16.5% of GDP. Total exports in the country amounted to 31.8% of GDP.

The most intensive use of electricity is found within the electric power industry. Consumption within the electric power industry includes use in administrative facilities and in generating facilities, transportation loses have been excluded. Beyond consumption in the electric power industry, the sectors of economic activity in which electricity bills represent the largest share of input costs are the manufacture of paper and paper products, chemical and chemical products, libraries, archives, museums and other cultural activities, manufacture of non-metallic mineral products, mining and quarrying, the manufacture of basic metals, fishing and aquaculture, accommodation and the manufacture of textiles. Various services, including hotels and accommodation, food services, and recreational activities have relatively large electric power bills.

Household Income and Expenditure

Households consume energy to satisfy demand for transportation services and for residential use. Residential energy consumption accounted for 3.91% of household expenditure while energy demand for personal transportation accounted for 4.55% of household expenditure. Diesel fuel is the dominant source of fuel for automobile transportation in Portugal, accounting for 56.9% of energy consumption in transportation. Residential energy demand includes the use of electricity for heating (11.1% of expenditure) and cooling (0.7%) the residence, heating water (27.4%), energy consumption in the kitchen (39.7%), associated with electrical appliances (15.0%) and lighting (6.1%). Residential demand for energy is dominated by electricity consumption, which accounts for 42.5% of consumption and 62.5% of expenditure on energy across households. Butane, propane and liquefied petroleum gases (LPG) are also an important source of energy in residences accounting for 18.0% of consumption and 24.3% of expenditure. These are particularly important sources of energy for hot water furnaces and for use in cooking in the kitchen. Natural gas use in residences has increased in recent years but remains relatively modest accounting for 9.3% of consumption and 6.1% of expenditures. Coal is used in small amounts in households and almost exclusively for cooking.

Patterns of energy consumption across household groups at different income levels tend to suggest that energy services are normal goods, whose consumption increases with income, and that these are necessary goods, that they tend, generally to make up a larger share of a household's budget at lower levels of income than at higher levels of income. This pattern of consumption is particularly apparent for electricity demand. Expenditure on electricity amounted to 4.04% (3.91%) of expenditure for households in the lowest income quintile in 2010, 3.49% (3.11%) for those in the second quintile, 3.07% (2.69%) for those in the third quintile, 2.63% (2.26%) for those in the fourth quintile and 2.25% (1.70%) for those in the highest income quintile. Natural gas consumption tends to follow a similar pattern of expenditures, though expenditures in the lowest income quintile are slightly lower (0.42% of income) than those in the second (0.56%) and third (0.45%) of income. Expenditure on natural gas for households in the highest two income quintiles is somewhat lower, at 0.29% and 0.10% of income, respectively.

Much of Portugal, and the larger cities of Lisbon and Porto, in particular, is equipped with a well-developed public transportation system, which includes buses, trains, boats and light rail networks. The availability of this public transportation network coupled with high gasoline and diesel prices, lower salaries, and the relatively compact city structures have contributed towards making cars something of a luxury, though expenditure shares vary little across income groups. Diesel and gasoline consumption together account for 4.32% of expenditure among low income households, 4.49% among households in the second income quintile, 4.55% among those in the third income quintile, 4.63% among those in the fourth income quintile and 4.57% among those in the highest income quintile.

The Public Sector

Since 2005, public debt has exploded from 67.4% of GDP to 130.6% of GDP in 2014. Public deficits in Portugal reached 6.8% of GDP in 2009 and 8.2% of GDP in 2010.

The tax burden in Portugal amounted to 34.5% of GDP in 2015. In recent years, the increase in taxation in the context of austerity measures to address high levels of public indebtedness have focused on increases in the corporate income tax, the value added tax and social security contributions. The tax burden in Portugal was below the EU28 average of 39.0% in 2015. Taxes on income, including personal income taxes (9.27%) and social security contributions (7.98% of GDP from employers and 3.74% from workers) are the largest source of revenue for the Portuguese government. Value added and excise taxes are the second largest source of income for the Portuguese government. Revenues from the value added tax amounted to 8.0% of GDP between 2005 and 2014 and product specific excise taxes, including taxes on energy products amounted to 4.37% of GDP.

Table A1 – Basic Household Data

	Number of Households	Weekly After Tax Income	Labor Income	Interest Income	Transfers	Savings
All	4,044,100	366 €	249 €	8 €	109 €	66 €
1º quintile	805,048	143 €	68 €	0 €	75 €	0 €
2º quintile	797,644	219 €	128 €	1 €	91 €	9 €
3º quintile	817,872	280 €	189 €	2 €	89 €	25 €
4º quintile	811,422	388 €	288 €	4 €	96 €	54 €
5º quintile	812,114	797 €	571 €	32 €	194 €	274 €

Table A2 – Basic Industry Data

Units: % of GDP	GDP	Private Consumption	Public Consumption	Gross Fixed Capital Formation	Exports	Imports
Economy-Wide	100.00	66.00	21.00	20.00	29.00	36.00
Crude Oil	-3.50	0.00	0.00	0.00	0.00	3.50
Coal	-0.16	0.02	0.00	0.00	0.00	0.18
Natural Gas	-0.93	0.20	0.00	0.00	0.00	1.13
Propane	0.40	0.40	0.00	0.00	0.00	0.00
Butane	0.10	0.10	0.00	0.00	0.00	0.00
LPG	0.10	0.10	0.00	0.00	0.00	0.00
Fuel Oil	0.00	0.00	0.00	0.00	0.00	0.00
Gasoline	1.48	1.25	0.20	0.00	0.45	0.43
Diesel	2.38	1.75	0.60	0.00	1.00	0.98
Electricity	2.65	1.60	1.20	0.00	0.05	0.20
Biomass	0.10	0.10	0.00	0.00	0.00	0.00
Agriculture	1.85	2.50	0.15	0.25	0.60	1.65
Equipment	2.18	1.50	0.13	3.00	3.40	5.85
Construction	10.89	0.10	0.59	10.00	0.30	0.10
Transportation	5.30	1.50	1.90	0.00	2.65	0.75
Textiles	5.52	4.75	0.07	0.00	3.00	2.30
Wood, pulp and paper	1.50	0.50	0.15	0.00	1.85	1.00
Chemicals and pharmaceuticals	1.29	2.00	1.74	0.00	1.70	4.15
Rubber, plastic and ceramics	1.10	0.40	0.10	0.00	2.00	1.40
Primary metals	0.13	0.20	0.13	0.25	2.25	2.70
Other	66.50	47.03	12.91	6.50	9.75	9.69

Table A3 - Trade Exposure by Sector of Economic Activity

	Exports (% of GDP)	Imports (% of GDP)	Net Exports (X-M)	Import Share of Domestic Demand (%)
Crude Oil		3.500	-3.500	100.00
Coal		0.183	-0.183	100.00
Natural Gas		1.125	-1.125	100.00
Propane				0.00
Butane				0.00
LPG				0.00
Fuel Oil				0.00
Gasoline	0.450	0.425	0.025	35.42
Diesel	1.000	0.975	0.025	33.62
Electricity	0.050	0.200	-0.150	2.45
Biomass				0.00
Agriculture	0.600	1.650	-1.050	23.67
Equipment	3.400	5.850	-2.450	85.28
Construction	0.300	0.100	0.200	0.75
Transportation	2.650	0.750	1.900	9.04
Textiles	3.100	2.300	0.800	33.67
Wood, pulp and paper	1.850	1.000	0.850	27.93
Chemicals and pharmaceuticals	1.700	4.150	-2.450	58.25
Rubber, plastic and ceramics	2.000	1.400	0.600	38.10
Primary metals	2.250	2.700	-0.450	51.87
Other	9.650	9.692	-0.042	8.29