On the environmental, economic and budgetary impacts of fossil fuel prices: A dynamic general equilibrium analysis of the Portuguese case *

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Abstract

This paper examines the environmental, economic and budgetary impacts of fuel prices using a dynamic general equilibrium model of the Portuguese economy which highlights the mechanisms of endogenous growth and includes a detailed modeling of the public sector. The fuel price scenarios are based on forecasts by the DOE-US, the IEA-OECD and IHS Global Insight Inc., and represent a wide range of projections for absolute and relative fossil fuel prices. The dramatic differences in relative prices lead to substantially different environmental impacts. Our results suggest that higher fuel prices in the DOE-US scenario would lead to a reduction in emissions that account for 10.2% of the implicit emissions deficit for EU 2020 emissions targets, while relative price changes, led by lower prices for coal, result in a 19.2% increase for the IEA-OECD scenario. Under the IHS scenario, declining fuel prices would increase the emissions deficit by 95.9%. In terms of the long term economic impact, our results suggest a 2.2% drop in GDP in the DOE-US scenario and of 1.9% in the IEA-OECD scenario and an increase of 1.4% in the IHS scenario, which reflect the absolute change in energy costs. As to the budgetary impact, higher fuel prices lead to lower tax revenues, which, coupled with a reduction in public spending translates to lower public deficits. In addition, and from a methodological perspective, our results highlight the importance of endogenous growth mechanisms. A scenario of higher fuel prices would, under exogenous economic growth assumptions, result in larger baseline emissions growth scenarios, substantially smaller economic effects, and rather different budgetary effects. Finally, and from a policy perspective, our results highlight the impact of fossil fuel prices in defining the level of policy intervention required for compliance with international and domestic climate change legislation. As a corollary, we argue that it is critical for both international comparisons and international policy negotiations to define baseline emission targets in function of steady state economic projections under stable price assumptions.

Keywords: Fuel Prices, Endogenous Growth, Budgetary Consolidation, Climate Policy, Dynamic General Equilibrium, Portugal.

JEL Classifications: Q40, Q43, Q54, C68, D58, H50, H68.

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1. Introduction

This paper addresses the impact of fossil fuel prices on economic activity, the public sector account, energy consumption and carbon dioxide (CO_2) emissions using a dynamic general equilibrium model of the Portuguese economy, an economy dependent on foreign energy sources. This study has two main purposes. The first is to assess the role of fuel prices as drivers of CO_2 emissions. The second is to explore the dynamic relationship between fuel prices, economic activity, and the evolution of the public account. This is particularly important in a policy environment dominated by concerns about budgetary sustainability. These two objectives together allow us to determine the impact of fuel prices on climate policy efforts.

Fuel prices are important in climate policy due to their direct and indirect impact on CO_2 emissions. Fuel prices directly affect emissions through their impact on energy costs, energy demand, and as drivers in the adoption of new energy technologies. This direct effect has been widely recognized in applied policy analysis. High fossil fuel prices reduce energy demand and can stimulate energy efficiency and the adoption of renewable energy technologies, leading to a reduction in emissions [see Martinsen et al (2007)]. Relative price levels, however, may favor a greater use of coal in electric power and synthetic fuels in transportation, increasing emissions [see van Ruijven and van Vuuren (2009)]. As a consequence, fuel price forecasts are a key input for emissions projections [see Brecha (2008), Nel and Cooper (2009), Verbruggen and Marchohi (2010), and UK Department of Energy and Climate Change (2010)]

Fuel prices also indirectly affect emissions through their impact on economic growth and the dynamic feedback between growth and energy demand [see van Ruijven and van Vuuren (2009)]. This indirect impact of fuel prices on emissions growth is not typically considered in applied climate policy analysis. Still, a great deal of empirical research has highlighted the dynamic relationship between energy prices, consumption and growth [see Hamilton (2009), He et al. (2010), Korhonen and Ledyaeva (2010), and Balcilar et al. (2010)]. As a result, energy prices are considered to be an important input for macroeconomic forecasting [see Esteves and Neves (2004), Roeger (2005), and European Commission (2010b)].

The fact that fuel prices affect economic activity is important in itself [see Backus and Crucini (2000) and Schubert and Turnovsky (2010)]. Overall, fuel prices affect economic performance both in terms of economic growth and of its dynamic feedbacks with the public sector account. These two links are fundamental since they directly correlate to some of the most important policy constraints faced by many energy-importing economies in their pursuit of sound climate policies: the need to enact policies that promote long-term growth and fragile public budgets. These policy constraints are particularly relevant for the less developed energy-importing economies in the European Union (EU). As EU structural transfers have shifted towards new member states, countries such as Ireland, Greece, and Portugal, have been forced to rely on domestic public policies to promote real convergence to EU standards of living. This poses a challenge since growing public spending and, more recently, falling tax revenues and countercyclical policies have contributed to a fast increasing public debt and a sharp need for budgetary consolidation. Furthermore, the need for fiscal responsibility is ever present in the context of the Stability and Growth Programs these countries are subject to in the framework of their participation in the Euro zone.

The wide ranging economic and environmental impacts of energy prices highlight the need for an integrated assessment of the economic and environmental impact of fuel prices. In this paper, we examine the impact of different fuel price scenarios using a dynamic general equilibrium model. We focus on primary energy demand by firms and CO_2 emissions from fossil fuel combustion activities because these are a linear function of the quantity of fossil fuels consumed. Fossil fuels are imported while investment in wind energy is privately financed.

The fuel price scenarios are based on forecasts by the US Department of Energy (DOE-US), the OECD International Energy Agency (IEA-OECD) and IHS Global Insight Inc. (IHS), which are widely used in policy analysis and macroeconomic forecasting exercises. Naturally, the DOE-US forecasts are commonly used by the US government while the IEA-OECD forecasts are most commonly used in the EU. In addition, these fuel price forecasts correspond to, sometimes dramatically, different scenarios which allow us to examine the impact of differences in the relative price of fossil fuels as well as absolute price levels.

In turn, our model incorporates fully dynamic optimization behavior, endogenous growth, and a detailed modeling of the public sector activities, both tax revenues and consumption and investment spending. The model is calibrated to replicate the stylized facts of the Portuguese economy over the last decade. Previous versions of this model have been used to evaluate the impact of tax policy [see Pereira and Rodrigues (2002, 2004)] and social security reform [see Pereira and Rodrigues (2007)]. This model brings together two important strands of the taxation literature [see the above applications of this model for a detailed list of the references]. On one hand, it follows in the footsteps of computable general equilibrium modeling. It shares with this literature the ability to consider the tax system in great detail. This is important given the evidence that the costs and effectiveness of climate policies are influenced by existing tax distortions [see Goulder (1995), Goulder et al (1999) and Goulder and Parry (2008)]. On the other hand, it incorporates many of the insights of the endogenous growth literature. In particular, it recognizes that public policies have the potential to affect the fundamentals of long term growth and not just for generating temporary level effects [see Xepapadeas (2005)].

The key distinguishing feature of our model in the applied climate policy literature is our focus on endogenous growth and the associated treatment of public sector optimization behavior [see Conrad (1999) and Bergman (2005) for literature surveys]. Productivity enhancing public sector investment in public capital and human capital, which have been largely overlooked in applied climate policy [Carraro et al. (2009)], are, in addition to private investment, the drivers of endogenous growth. Indeed, few climate policy models consider endogenous growth mechanisms, with the notable exception of the computable DICE model and several analytical models [Bovenberg and de Mooij (1997), Fullerton and Kim (2008) and Glomm et al. (2008)]. Furthermore, the analysis of the interaction between fiscal policies, public capital, economic growth, and environmental performance has garnished little attention and then only in a theoretical framework [Greiner (2005) and Gupta and Barman (2009)].

The remainder of this paper is organized as follows. Section 2 provides a description of the dynamic general equilibrium model and implementation issues. Section 3 presents the fuel prices scenarios. Section 4 discusses the economic and budgetary impact of fuel prices and section 5 discusses the impact of fuel prices on the energy sector and CO_2 emissions. Section 5 also discusses the policy implications of this research. Section 6 provides a sensitivity analysis and discusses methodological issues. Finally, section 7 concludes.

2. The Dynamic General Equilibrium Model

We consider a decentralized economy in a dynamic general-equilibrium framework. All agents are price-takers and have perfect foresight. With money absent, the model is framed in real terms. There are four sectors in the economy – the production sector, the household sector, the public sector and the foreign sector. The first three have an endogenous behavior but all four sectors are interconnected through competitive market equilibrium conditions, as well as the evolution of the stock variables and the relevant shadow prices. All markets are assumed to clear.

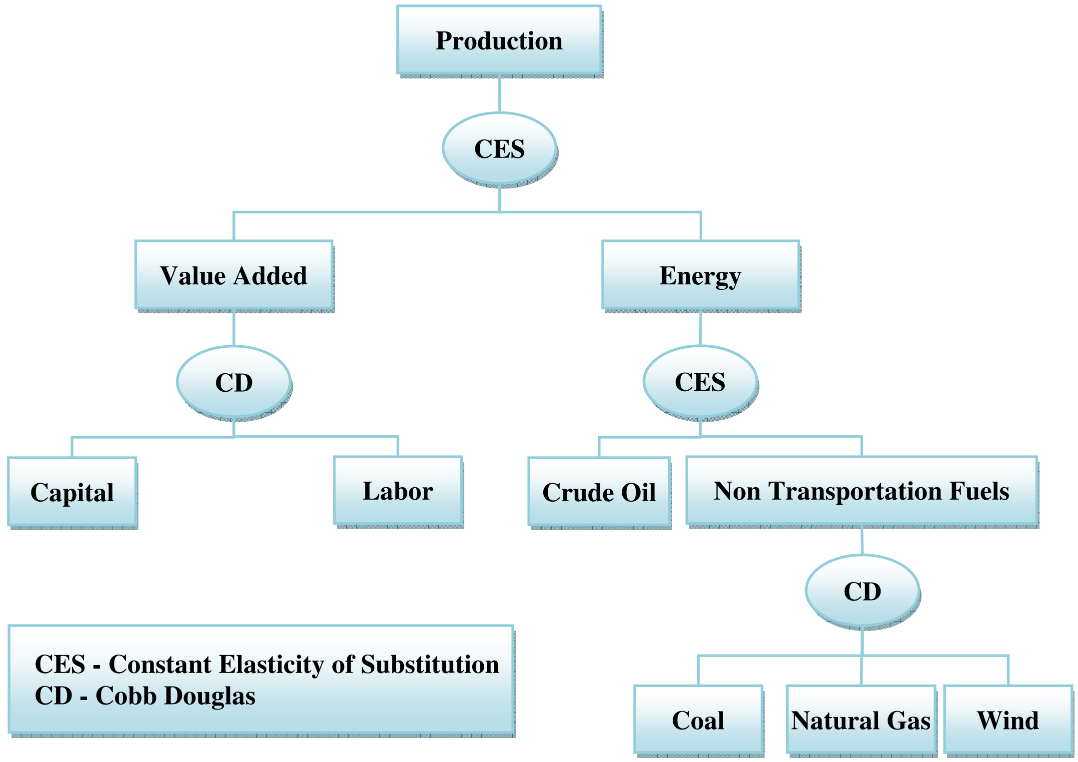
The trajectory for the economy is described by the optimal evolution of eight stock and five shadow price variables - private capital, wind energy capital, public capital, human capital, and public debt together with their shadow prices, and foreign debt, private financial wealth, and human wealth. In the long term, endogenous growth is determined by the optimal accumulation of private capital, public capital and human capital. The last two are publicly provided.

2.1. The Production Sector

Figure 1 presents an overview of the production structure of the economy. Aggregate output, Y_t, is produced with a CES technology, as in (Eq. 1), linking value added, VA_t, and aggregate primary energy demand, AGG_E_t. Value added is produced with a Cobb-Douglas technology (Eq. 2), exhibiting constant returns to scale in the reproducible inputs – effective labor, $L_t^d HK_t$, private capital, K_t, and public capital, KG_t. Only the demand for labor, L_t^d, and the private capital stock are directly controlled by the firm, meaning that if public investment is absent then decreasing returns set in. Public infrastructure and the economy-wide stock of knowledge, HK_t, are publicly financed and are positive externalities. The capital and labor shares are $\theta_K$and θ_L, respectively, and $\theta_{KG} = 1 - \theta_K - \theta_L$ is a public capital externality parameter. A is a size parameter.

Private capital accumulation is characterized by (Eq. 3) 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

Figure 1: Overview of the Production Structure



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.

The firms' net cash flow, NCF, (Eq. 4), represents the after-tax position when revenues from sales are netted of wage payments and investment spending. The after-tax net revenues reflect the presence of a private investment and wind energy investment tax credit at an effective rate of τ_{ITC} and τ_{ITCR}, respectively, taxes on corporate profits at a rate of τ_{CIT}, and Social Security contributions paid by the firms on gross salaries, $w_t L_t^d HK_t$, at an effective rate of τ_{FSSC}.

Buildings make up a fraction, $0 < (1 - \rho_I) < 1$, of total private investment expenditure. Only this fraction is subject to value-added and other excise taxes, the remainder is exempt. This situation is modeled by assuming that total private investment expenditure is taxed at an effective rate of $\tau_{VATET,I}$. The corporate income tax base is calculated as Y_t net of total labor costs,

$(1+\tau_{FSSC})w_t L_t^d HK_t$, and net of fiscal depreciation allowances over past and present capital investments, αI_t. A straight-line fiscal depreciation method over $NDEP$ periods is used and investment is assumed to grow at the same rate at which output grows. Under these assumptions, depreciation allowances simplify to αI_t, with α is obtained by computing the difference of two infinite geometric progression sums, and is given by (Eq. 5).

Optimal production behavior consists in choosing the levels of investment and labor that maximize the present value of the firms' net cash flows, (Eq. 4), subject to the equation of motion for private capital accumulation, (Eq. 3). The demands for labor and investment are given by (Eq. 6) and (Eq. 7), respectively, and are obtained from the current-value Hamiltonian function, where q_{t+1}^K is the shadow price of private capital, which evolves according to (Eq. 8). 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 is transferred to the consumers.

2.2. The Energy Sector

The energy sector is an integral component of the firms' optimization decisions. Aggregate primary energy demand is produced with CES technology (Eq. 9) in which crude oil, $CrudeOil_t$, and non-transportation fuels, NTF_t are substitutable at a lower rate reflective of the dominance of petroleum products in transportation energy demand and the dominance of coal, natural gas and, to a lesser extent, wind energy, in electric power and industry. Non-transportation fuels are produced with a Cobb-Douglas technology (Eq. 15) recognizing the relatively greater potential substitution effects in electric power and industry. The accumulation of wind energy infrastructure is characterized by (Eq. 16) where the physical capital, wind turbines, depreciate at a rate of δ_{RK}. Gross investment in wind energy infrastructure, RI_t, is dynamic in nature and is subject to adjustment costs as private capital.

Optimal primary energy demand is derived from the maximization of the present value of the firms' net cash flows as discussed above. The first order condition for crude oil demand and non-transportation energy demand are given by (Eq. 13) and (Eq. 14). In turn, the demand for coal and natural gas are defined through the nested dual problem of minimizing energy costs (Eq. 10) given the production function (Eq. 15) and optimal demand levels given in (Eq. 13), yielding (Eq. 12). Finally, the variational condition for optimal wind energy investment is given in (Eq. 17) and the equation of motion for the shadow price of wind energy is given in (Eq. 18).

The hydrogen and carbon contained in fossil fuels generates the potential for heat and energy production. Carbon is released from the fuel upon combustion; 99.0% of the carbon released from the combustion of petroleum, 99.5% from natural gas, and 98.0% from coal, oxidizes to form CO_2. Together, the quantity of fuel consumed, its carbon factor, oxidation rate, and the ratio of the molecular weight of CO_2 to carbon are used to compute the amount of CO_2 emitted from fossil fuel combustion activities in a manner consistent with the Intergovernmental Panel for Climate Change (2006) reference approach. These considerations suggest a linear relationship between CO_2 emissions and fossil fuel combustion activities. Computation of CO_2 emissions from fossil fuel combustion is given in (Eq. 19).

2.3. The Households

An overlapping-generations specification was adopted in which the planning horizon is finite but in a non-deterministic fashion. A large number of identical agents are faced each period with a probability of survival, γ. The assumption that γ is constant over time and across age-cohorts yields a perpetual youth specification in which all agents face a life expectancy of $\frac{1}{1-\gamma}$. Without loss of generality, the population, which is assumed to be constant, is normalized to one. Therefore, per capita and aggregate values are equal.

The household, aged a at time t, chooses consumption and leisure streams that maximize intertemporal utility, (Eq. 20), subject to the consolidated budget constraint, (Eq. 21). The objective function is lifetime expected utility subjectively discounted at the rate of β. Preferences, $u_{a+v,t+v}$, are additively separable in consumption and leisure, and take on the CES form where B is a size parameter and σ is the constant elasticity of substitution. The effective subjective discount factor is $\gamma\beta$ meaning that a lower probability of survival reduces the effective discount factor making the household relatively more impatient.

The budget constraint, (Eq. 21), 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, $TW_{a,t}$. The loan rate at which households borrow and lend among themselves is $1/\gamma$ times greater than the after-tax interest rate reflecting the probability of survival.

For the household of age a at t, total wealth, $TW_{a,t}$ (Eq. 22), is age-specific and is composed of human wealth, $HW_{a,t}$, net financial worth, $FW_{a,t}$, and the present value of the firm, PVF_t. Human wealth (Eq. 23), represents the present discounted value of the household's future labor income stream net of personal income taxes, τ_{PIT}, and workers' social security contributions, τ_{WSSC}. Labor's reward per efficiency unit is w_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, that is augmented by public investment on education. Labor earnings are discounted at a higher rate reflecting the probability of survival.

A household's income is augmented by net interest payments received on public debt, PD_t, profits distributed by corporations, NCF_t, international transfers, R_t, and public

Table 1: The Dynamic General Equilibrium Model - The Model Structure

The Production Sector

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

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

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

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

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

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

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

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

The Energy Sector

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

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

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

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

$$\theta_E \frac{AGG\_E_t}{FE_t} A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})AGG\_E_t^{\rho_{va}}\right)^{1/\rho_{va}-1}(1-\gamma_E)\, A_{E,t}\left(\gamma_E\, Crude\ Oil_t^{\rho_e} + (1-\gamma_E)\, NTF_t^{\rho_e}\right)^{1/\rho_e-1} NTF_t^{\rho_e} - p_{fe,t} = 0 \quad (13)$$

$$\frac{AGG\_E_t}{Crude\ Oil_t}(1-\gamma_{VA})A_t\left(\gamma_{va}\, VA_t^{\rho_{va}} + (1-\gamma_{va})AGG\_E_t^{\rho_{va}}\right)^{1/\rho_{va}-1}\gamma_E\, A_{E,t}\left(\gamma_E\, Crude\ Oil_t^{\rho_e} + (1-\gamma_E)\, NTF_t^{\rho_e}\right)^{1/\rho_e-1} Crude\ Oil_t^{\rho_e} - p_{crude\ oil,t} = 0 \quad (14)$$

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

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

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

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

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

Table 1 (con't): The Dynamic General Equilibrium Model - The Model Structure

The Household Sector

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

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

$$TW_{a,t}\equiv HW_{a,t}+FW_{a,t}+PVF_t \quad (22)$$

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

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

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

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

The Public Sector

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

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

$$T_t=PIT_t+CIT_t+VAT_t+FSSC_t+WSSC_t+LST_t \quad (29)$$

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

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

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

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

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

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

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

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

Market Equilibrium

$$(1-UR_t)LS_t=L_t^d \quad (38)$$

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

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

$$FW_t=PD_t-FD_t \quad (41)$$

transfers, TR_t. On the spending side, debts to foreigners are serviced, taxes are paid and consumption expenditures are made. Income net of spending adds to net financial wealth (Eq. 24). Under the assumption of no bequests, households are born without any financial wealth. In general, total wealth is age-specific due to age-specific labor supplies and consumption streams.

Assuming a constant real interest rate, the marginal propensity to consume out of total wealth is age-independent and aggregation over age cohorts is greatly simplified. Aggregate consumption demand is given by (Eq. 25) and an age-independent coefficient enables us to write the aggregate demand for leisure, (Eq. 26), as a function of aggregate consumption.

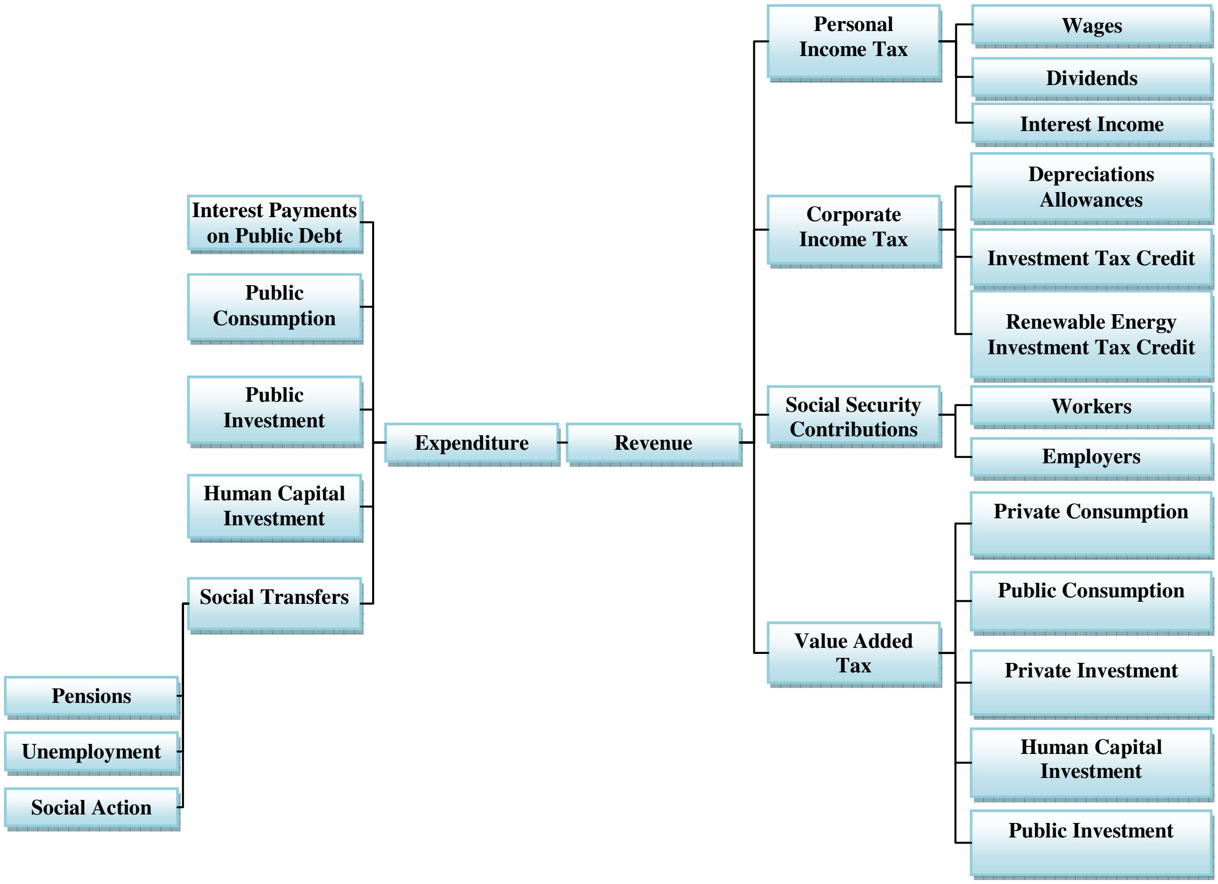
2.4. The Public Sector

The equation of motion for public debt, PD_t, (Eq. 28), reflects the fact that the excess of government expenditures over tax revenues has to be financed by increases in public indebtedness. Total tax revenues, T_t, (Eq. 29) include personal income taxes, PIT_t, corporate income taxes, CIT_t, value added taxes, VAT_t, social security taxes levied on firms and workers $FSST_t$ and $WSST_t$. All of these taxes are levied on endogenously defined tax bases. Residual taxes are modeled as lump sum, LST_t, and are assumed to grow at an exogenous rate.

The public sector pays interest on public debt at a rate of r_t^{PD} and transfers funds to households TR_t in the form of pensions, unemployment subsidies, and social transfers, which grow at an exogenous rate. In addition, it engages in public consumption activities, CG_t, and public investment activities in both public capital and human capital, IG_t and IH_t.

Public investments are determined optimally, respond to economic incentives, and constitute an engine of endogenous growth. The accumulations of HK_t and KG_t are subject to depreciation rates, δ_{HK} and δ_{HK}, and to adjustment costs that are a fraction of the respective investment levels. The adjustment cost functions are strictly convex and quadratic.

Figure 2: Overview of the Public Sector



Public sector decisions consist in choosing the trajectories for CG_t, IH_t, and IG_t that maximize social welfare, (Eq. 27), defined as the net present value of the future stream of utility derived from public consumption, parametric on private sector consumption-leisure decisions. The optimal choice is subject to three constraints, the equations of motion of the stock of public debt, (Eq. 28), the stock of public capital, (Eq. 30), and the stock of human capital, (Eq. 31).

The optimal trajectories depend on q_{t+1}^{PD}, q_{t+1}^{KG}, and q_{t+1}^{HK}, the shadow prices of the public debt, public capital, and human capital stocks, respectively. The relevant discount rate is $1+(1-\tau_r)r_{t+1}^{PD}$ because this is the financing rate for the public sector. Optimal conditions are (Eq. 32) for public debt, (Eq. 33) for public consumption, (Eq. 34-35) for public investment, and (Eq. 36-37) for investment in human capital.

2.5. The Foreign Sector

The equation of motion for foreign financing, FD_t, (Eq. 40), provides a stylized description of the balance of payments. Domestic production, Y_t, and imports are absorbed by domestic expenditure and exports. Net imports, $-NX_t$, (Eq. 39), are financed through foreign transfers, R_t, and foreign borrowing. Foreign transfers grow at an exogenous rate. In turn, 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, r_t^{FD}, which is determined in the international financial markets. This is the prevailing rate for all domestic agents.

2.6. The Intertemporal Market Equilibrium

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 (Eq. 38-41). The labor-market clearing condition is given by (Eq. 38) where a structural unemployment rate of UR_t is exogenously considered. The product market equalizes demand and supply for goods and services. Given the open nature of the economy, part of the demand is satisfied through the recourse to foreign production, hence (Eq. 39) and (Eq. 40). Finally, the financial market equilibrium, (Eq. 41), reflects the fact that private capital formation and public indebtedness are financed by household savings and foreign financing.

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 g while market prices and shadow prices are constant. There are three types of restrictions imposed by the existence of a steady-state. First, it determines the value of critical production parameters, like 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 public account deficit and the current account deficit are a fraction g of the respective stocks of debt. Finally, the exogenous variables, such as public transfers or international transfers, have to grow at the steady-state growth rate.

2.7. Dataset, Parameter Specification, and Calibration

The model is implemented numerically using detailed data and parameters sets. The dataset is reported in Table 2 and reflects the GDP and stock variable values in 2008; public debt and foreign debt reflect the most recent available data. The decomposition of the aggregate variables follows the average for the period 1990–2008. This period was chosen to reflect the most recent available information and to cover several business cycles, thereby reflecting the long-term nature of the model. In turn, the baseline energy and environmental accounts are presented in Table 3. The baseline primary demand for crude oil grows to 658.7 PJ, coal demand to 169.1 PJ and demand for natural gas to 158.0 PJ in 2020. These lead to a baseline projection for emissions of 71.9 Mt CO_2 in 2020.

Parameter values are reported in Table 4 and are specified in different ways. Whenever possible, parameter values are taken from the available data sources or the literature. This is the case, for example, of the population growth rate, the probability of survival, the share of private consumption in private spending, the output scale parameter, and the different effective tax rates. In turn, consistent with the conditions for the existence of a steady-state, the exogenous variables, as mentioned above, were set to grow at the observed long-term steady-state growth rate. These parameters play no direct role in the model calibration.

All the other parameters are obtained by calibration; i.e., in a way that the trends of the economy for the period 1990–2008 are extrapolated as the steady-state trajectory. These

Table 2: 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
Public sector data (% of Y_0)		
T_0	Total tax revenue	41.958
PIT_0	Personal income tax revenue	5.710
CIT_0	Corporate income tax revenue	3.110
VAT_0	Value added tax revenue	13.700
VAT_c	on private consumption expenditure	10.669
VAT_I	on private investment expenditure	1.902
VAT_{cg}	on public consumption expenditure	0.649
VAT_{ig}	on public capital investment expenditure	0.379
VAT_{ih}	on public investment in human capital	0.101
$WSSC_0$	Social security tax revenues	11.700
$WSSC_{1,0}$	employers contributions	5.600
$WSSC_{2,0}$	workers contributions	6.100
$Carbon\ Tax_0$	Carbon 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

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

Population and employment data (% of POP_0)			
	POP_0	Population (in thousands)	10.586
	L_0	Active population	5.587
	UR_0	Unemployment rate	0.058
Private Wealth (% of Y_0)			
	HW_0	Human wealth	2574.498
	FW_0	Financial wealth	-22.700
	PVF_0	Present value of the firm	1429.101
	NCF_0	Distributed profits	17.930
Prices			
	w_0	Wage rate	0.031
	q_0^{PD}	Shadow price of public debt	-0.883
	q_0^k	Shadow price of private capital	1.291
	q_0^{rk}	Shadow price of wind energy capital	1.291
	q_0^{kg}	Shadow price of public capital	1.104
	q_0^{hk}	Shadow price of human capital	5.521
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 3: Baseline Energy and Environmental Accounts

	Primary Energy Demand (PJ)				
	2010	**2020**	**2030**	**2040**	**2050**
Crude Oil	553.1	658.8	784.6	934.4	1112.8
Coal	142.0	169.1	201.4	239.9	285.7
Natural Gas	132.7	158.0	188.2	224.1	266.9
Wind Energy	22.3	26.6	31.7	37.7	44.9
	CO_2 Emissions from Fossil Fuel Combustion Activities (Mt CO_2)				
	2010	**2020**	**2030**	**2040**	**2050**
Crude Oil	40.2	47.8	57.0	67.8	80.8
Coal	12.8	15.3	18.2	21.6	25.8
Natural Gas	7.4	8.8	10.5	12.5	14.9
Total	60.4	71.9	85.6	102.0	121.5

Table 4: The Dynamic General Equilibrium Model – The Structural Parameters

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

Table 4 (con't): The Dynamic General Equilibrium Model – The Structural Parameters

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

calibration parameters assume two different roles. In some cases, they are chosen freely in that they are not implied by the state-state restrictions. This is the case, for example, of the discount rate, the inter-temporal elasticity of substitution, the elasticities of substitution, the shares for labor and capital in production, and the public capital externality. Although free, these parameters have to be carefully chosen since their values affect the value of the remaining calibration parameters. Accordingly, they were chosen either using central values or using available data as guidance. The remaining calibration parameters are obtained using the steady-state restrictions as discussed above.

3. On the Fuel Price Scenarios

The fuel price scenarios we consider are based on forecasts developed by the US Department of Energy, (DOE-US), the International Energy Agency (IEA-OECD) and IHS Global Insight, Inc. (IHS) as presented in the *Annual Energy Outlook* of the US Department of Energy (2010). Table 5 presents the data for each of the forecasts including a composite energy price index and relative price ratios.

Each of the price scenarios presents a range of different level and relative price movements by 2035, including changes in crude oil prices of 33.8%, 18.3% and -19.6%, in coal prices of 1.8%, -9.3% and -27.3% and in natural gas prices of 0.1%, 35.9%, and -7.3%, in the

Table 5: Fuel Price Scenarios

(2008=100.00)

	2010	2020	2030	2040	2050
	DOE-US				
Reference Price Composite	97.89	102.11	114.67	128.06	134.42
Petroleum and its Products	98.55	108.75	124.03	140.08	147.81
Coal	99.42	96.72	98.90	102.70	103.80
Natural Gas	93.52	80.18	92.49	105.11	111.33
Coal/Natural Gas Ratio	106.31	120.63	106.93	97.71	93.23
Oil/Natural Gas Ratio	99.12	112.43	125.41	136.40	142.40
	IEA-OECD				
Reference Price Composite	96.79	102.36	116.40	122.17	129.27
Petroleum and its Products	96.91	102.89	118.32	124.67	132.48
Coal	93.00	86.38	90.72	92.51	94.70
Natural Gas	100.39	117.25	135.85	143.50	152.91
Coal/Natural Gas Ratio	92.64	73.67	66.78	64.46	61.93
Oil/Natural Gas Ratio	104.20	119.12	130.43	134.77	139.88
	IHS Global Insight				
Reference Price Composite	95.69	82.59	79.22	79.65	77.95
Petroleum and its Products	95.84	82.28	77.60	78.45	76.08
Coal	91.72	71.87	72.74	73.10	73.53
Natural Gas	99.30	95.37	92.93	91.68	90.45
Coal/Natural Gas Ratio	92.36	75.36	78.28	79.73	81.30
Oil/Natural Gas Ratio	104.50	114.49	106.69	107.33	103.47

DOE-US, IEA-OECD and IHS scenarios, respectively. Overall, the composite price index is forecasted to grow by 22.9% in the DOE-US scenario and by 16.4% in the IEA-OECD scenario and to decline by 19.0% in IHS scenario. To put these prices in perspective, the DOE-US prices scenario corresponds to an increase in the price of oil to $133.22 per barrel, the IEA-OECD to $115.00 per barrel while the IHS price scenario corresponds to a drop in the price of oil to $80.00 dollars per barrel. Accordingly, these scenarios allow us to explore the response to price increases and decreases across fuel price scenarios. After 2035, the end of the forecast horizons, we allow prices to grow at the average growth rate for the last ten years of the forecast.

While the change in the composite price index by 2020 is similar for the DOE-US and IEA-OECD scenarios, these scenarios differ markedly in the relative prices for coal and natural gas, with coal prices growing by 20.6% relative to natural gas prices in the DOE-US scenario and falling by 26.3% relative to natural gas prices in the IEA-OECD scenario. In addition, these two forecasts show a very different intertemporal evolution for coal and natural gas prices. Natural gas prices grow by more than any other fuel in the IEA-OECD forecast while the DOE-US forecast depicts an initial decline and subsequent increase in the price of natural gas, returning to 2008 levels by 2035. Coal prices, on the other hand, show a meaningful drop in price in the IEA-OECD price scenario, while remaining relatively stable in the DOE-US price scenario. Crude oil prices grow by the largest amount in the DOE-US price scenario. In turn, the IHS price projections are of a remarkably different character. Fuel prices are forecasted to fall and remain low, with a larger decline in the price of coal relative to that of oil and natural gas.

4. On the Impact of Fossil Fuel Prices on Energy Consumption and CO_2 Emissions

The energy sector impacts of the three price scenarios are presented in Tables 6, 7, and 8. Unless indicated otherwise, all figures are deviations from the steady state baseline and we focus on the impact in 2020, an important reference year for emissions targets in the EU. Where relevant due to important intertemporal variations, particularly for the DOE-US and IEA-OECD scenarios, we refer also to the impact in 2050.

4.1. On the Impact on Energy Consumption

Each of the fuel price scenarios illustrates a short term drop in fossil fuel prices followed, in the DOE-US and the IEA-OECD scenarios, with fuel price growth and, in the IHS fuel price scenario, with continued low prices. We will first focus on the DOE-US and IEA-OECD scenarios because of their similarities with respect to the long term growth in fuel prices.

Differences in relative prices between the DOE-US and IEA-OECD scenarios are particularly pronounced early in the model horizon. While by 2020 the composite energy price index increases by 1.5% in both the DOE-US and the IEA-OECD scenarios, we observe a 0.5% reduction in fossil fuel demand in the DOE-US scenario and a 1.2% increase in the IEA-OECD scenario. The growth in fossil fuel demand in the IEA-OECD price scenario results from the larger drop in fuel prices earlier in the model horizon coupled with the still substantial drop in the price of coal persisting beyond 2030. Furthermore, once changes in wind energy demand are accounted for, aggregate primary energy demand falls by 1.0% in the DOE-US scenario and increases by 1.4% in the IEA-OECD scenario. By 2050, however, primary energy demand falls in both the DOE-US and IEA-OECD scenarios, by 10.4% and 5.9%, respectively.

The important differences with respect to the aggregate impact on primary energy demand underscore important differences in the composition of energy demand. In particular, for the DOE-US scenario we observe an increase in natural gas consumption of 14.4%. This is due primarily to the 19.8% drop in natural gas price by 2020 together with the larger array of substitution possibilities for natural gas in industry and electric power. Indeed, the uptake in natural gas demand drives, in part, a 5.3% reduction in coal demand and a 11.2% reduction in 2010 and a 4.8% reduction in 2020 in investment in wind energy, driving an accumulated fall of 3.6% in the stock of wind energy infrastructure by 2020. The demand for crude oil by firms falls by 2.9%. In this scenario, therefore, we observe a shift in the energy mix towards natural gas.

Table 6 decomposes the energy sector impacts present for the DOE-US scenario into the effect of each fuel by considering each price trajectory, in isolation, in turn. The large reduction in natural gas prices early in the model horizon has a large and important impact on the demand for coal and wind energy resources. This results from the larger array of substitution possibilities

Table 6 Energy Sector Impacts for the DOE-US price scenario

(deviations from steady state)

	2010	**2020**	**2030**	**2040**	**2050**
Complete Price Scenario					
Primary Energy Demand	0.86	-1.00	-5.30	-8.86	-10.44
Crude Oil	1.00	-2.90	-8.96	-13.98	-16.37
Coal	-1.60	-5.33	-2.80	-1.98	-1.52
Natural Gas	4.78	14.39	4.34	-4.18	-8.16
Wind Energy Infrastructure	-1.08	-3.59	-2.66	-0.44	1.28
Decomposition of energy sector impacts					
Due to crude oil price changes alone					
Primary Energy Demand	0.65	-1.76	-5.46	-8.57	-10.13
Crude Oil	0.96	-3.02	-9.01	-13.94	-16.27
Coal	0.40	-0.03	-0.79	-1.56	-2.13
Natural Gas	0.40	-0.03	-0.79	-1.56	-2.13
Wind Energy Infrastructure	-0.01	-0.27	-0.80	-1.41	-1.98
Due to coal price changes alone					
Primary Energy Demand	0.05	0.30	0.10	-0.22	-0.30
Crude Oil	0.00	0.01	0.00	-0.01	-0.01
Coal	0.49	2.67	0.84	-2.20	-3.09
Natural Gas	-0.09	-0.53	-0.17	0.43	0.59
Wind Energy Infrastructure	-0.05	-0.16	-0.01	0.28	0.49
Due to natural gas price changes alone					
Primary Energy Demand	0.15	0.51	0.07	-0.07	0.01
Crude Oil	0.04	0.12	0.06	-0.04	-0.10
Coal	-2.46	-7.77	-2.83	1.81	3.83
Natural Gas	4.46	15.03	5.35	-3.08	-6.71
Wind Energy Infrastructure	-1.02	-3.16	-1.85	0.71	2.83

in industry and electric power generation. Over the long term, however, as natural gas prices return to their initial levels, crude oil price movements dominate the energy sector effects in the DOE-US scenario. An increase in crude oil prices alone has the same relative effect on coal and natural gas demand because, in the absence of relative price changes, the shift away from crude oil, together with the feedbacks from changes in economic activity levels, does not naturally differentiate between the consumption of these fuels.

The IEA-OECD scenario differs from the DOE-US scenario by considering, on one hand, substantially lower coal prices, falling 13.7% by 2020 and, on the other, much larger natural gas prices, growing 17.3% by 2020. As a result, we observe a 20.6% growth in the demand for coal and a drop in the demand for natural gas of 11.6%. The increase in natural gas prices contributes, in a very important way, to the 12.7% increase in investment in wind energy infrastructure, corresponding to an accumulated increase in the stock of wind turbines of 3.0% in 2020 and of 11.9% in 2050. Oil demand falls by 0.8% due to more limited technological substitution possibilities and smaller crude oil price movements.

Table 7 presents a decomposition of the effects of changes in the price of each fossil fuel in the IEA-OECD price scenario. This decomposition clearly shows the importance of increasing natural gas prices in stimulating coal demand and investment in wind energy infrastructure. Indeed, by 2050, over 75% of the increase in coal demand results from the substantial growth in natural gas prices. In addition, the entire increase in wind energy investment, tempered by the effects of falling coal prices and feedbacks from crude oil price increases, can be attributed to natural gas price increases in the IEA-OECD scenario.

The IHS scenario results in markedly different energy sector impacts since prices, in this case, are forecasted to fall. As a result, fossil fuel demand increases by 10.9% while primary energy demand falls by 8.6%. It shares with the IEA-OECD scenario a shift in relative prices that favors coal over natural gas. Under the IHS scenario, the demand for coal increases by 30.2% while demand for crude oil increases by 9.0%. In turn, demand for natural gas is 1.9% lower due to the drop in coal prices and the ease with which these can be substituted in industry and electric power. In addition, this contributes to a 4.1% drop in the stock of wind energy infrastructure.

Table 8 presents the decomposition of the energy sector impacts for the IHS price

Table 7 Energy Sector Impacts for the IEA-OECD price scenario

(Deviations from steady state)

	2010	2020	2030	2040	2050
Complete Price Scenario					
Primary Energy Demand	1.84	1.44	-2.57	-4.21	-5.90
Crude Oil	1.65	-0.77	-6.85	-9.58	-12.29
Coal	6.96	20.59	20.18	19.81	19.43
Natural Gas	-1.15	-11.60	-19.30	-22.73	-26.02
Wind Energy Infrastructure	0.36	3.03	6.71	9.61	11.91
Decomposition of energy sector impacts					
Due to crude oil price changes alone					
Primary Energy Demand	0.99	-0.43	-4.04	-5.74	-7.43
Crude Oil	1.58	-0.77	-6.71	-9.35	-11.96
Coal	0.33	0.08	-0.53	-1.02	-1.50
Natural Gas	0.33	0.08	-0.53	-1.02	-1.50
Wind Energy Infrastructure	0.01	-0.14	-0.52	-0.96	-1.40
Due to coal price changes alone					
Primary Energy Demand	0.72	1.52	0.87	0.66	0.44
Crude Oil	0.01	0.04	0.03	0.02	0.02
Coal	6.44	14.19	8.77	6.80	4.71
Natural Gas	-1.24	-2.57	-1.57	-1.22	-0.84
Wind Energy Infrastructure	-0.47	-1.44	-1.43	-1.21	-0.94
Due to natural gas price changes alone					
Primary Energy Demand	0.12	0.21	0.44	0.74	0.97
Crude Oil	0.06	-0.05	-0.18	-0.28	-0.38
Coal	0.15	5.54	11.09	13.34	15.80
Natural Gas	-0.23	-9.34	-17.57	-20.96	-24.25
Wind Energy Infrastructure	0.83	4.67	8.82	12.03	14.58

scenario for individual fuel price movements. The very large projected drop in coal prices is instrumental in defining the net impact of fuel prices in this scenario on the energy sector. In particular, the drop in coal prices drives reductions in natural gas demand, despite moderate price reductions for natural gas, and reductions in wind energy.

From these three scenarios and their decomposition it is immediately clear that cross price effects are particularly important in determining the impact of fuel prices on the energy

Table 8 Energy Sector Impacts for the IHS price scenario

(Deviations from steady state)

	2010	2020	2030	2040	2050
Complete Price Scenario					
Primary Energy Demand	1.71	8.63	9.99	9.78	10.70
Crude Oil	1.62	8.97	11.68	11.42	13.06
Coal	7.38	30.21	28.36	27.55	26.63
Natural Gas	-1.17	-1.87	0.48	1.68	2.94
Wind Energy Infrastructure	-1.02	-4.07	-5.60	-6.30	-6.64
Decomposition of energy sector impacts					
Due to crude oil price changes alone					
Primary Energy Demand	0.90	5.23	6.88	6.79	7.80
Crude Oil	1.64	8.88	11.54	11.24	12.86
Coal	-0.12	0.47	0.81	0.97	1.18
Natural Gas	-0.12	0.47	0.81	0.97	1.18
Wind Energy Infrastructure	0.07	0.39	0.68	0.92	1.13
Due to coal price changes alone					
Primary Energy Demand	0.83	3.48	3.22	3.12	3.04
Crude Oil	0.00	0.07	0.09	0.10	0.11
Coal	7.79	31.81	30.66	30.21	29.59
Natural Gas	-1.48	-5.27	-4.96	-4.83	-4.71
Wind Energy Infrastructure	-0.83	-3.19	-4.18	-4.53	-4.62
Due to natural gas price changes alone					
Primary Energy Demand	-0.02	0.00	0.00	-0.02	-0.01
Crude Oil	-0.01	0.02	0.04	0.06	0.08
Coal	-0.26	-1.68	-2.55	-2.97	-3.41
Natural Gas	0.44	3.11	4.87	5.82	6.78
Wind Energy Infrastructure	-0.27	-1.29	-2.14	-2.74	-3.21

sector. This is true for absolute price levels, but also for relative price levels.

4.2. On the Impact on CO_2 Emissions

Each scenario implies different levels of primary energy demand and a different composition of energy sources in demand. This has a natural impact on CO_2 emissions. As such, the three scenarios depict a wide range of potential emissions impacts. Price increases in the DOE-US scenario and a shift towards natural gas stimulate a 1.3% reduction in emissions in

2020. In turn, price changes that favor a shift towards coal in the IEA-OECD scenario generate a 2.4% increase in emissions in 2020. By 2050, however, the increasing price of fossil fuels reduces emissions by 12.2% and 7.2% in the DOE-US and IEA-OECD scenarios, respectively. Finally, a reduction in the price of all fossil fuels and a substantial shift towards coal and oil consumption in the IHS scenario results in a 12.2% increase in emissions by 2020.

Table 9 presents a decomposition of the emissions impact into the component attributable to individual fuel price movements. First, in the IEA-OECD price scenario, as with the energy sector impacts discussed above, the drop in coal prices by 2020 plays the dominant role in determining the net impact of fuel prices on CO_2 emissions. By 2050, however, crude oil price effects dominate. Here, natural gas price increases have a very small impact on emissions due to shifts in the energy sector which favor both coal and wind energy. Second, the increasing emissions in the IHS price scenario are driven by both crude oil and coal price reductions, due first to the large share of oil in primary energy demand and second to the higher emissions factor for coal and the associated drop in cleaner burning natural gas and carbon-free wind energy. As a result, in 2020, CO_2 emissions from fossil fuel combustion activities grow to 71.0 Mt CO_2 in the DOE-US prices scenario, 73.6 Mt CO_2 in the IEA-OECD price scenario and 80.6 Mt CO_2 in the IHS price scenario. These can be compared to our reference emissions levels of 71.9 Mt CO_2.

The reduction in CO_2 emissions implies an equivalent decrease in emissions per capita and in the emissions intensity of the economy. Emissions per capita are the largest in the IHS scenario, reaching 7.6 tCO_2 per person in 2020, followed by the IEA-OECD scenario at 6.9 tCO_2 per person and the DOE-US scenario at 6.7 tCO_2. Similarly, the emissions intensity of the economy is falling in those scenarios in which prices increase and growing in those scenarios in

Table 9 Decomposition of the Different Price Scenario: Emissions

(Deviations from steady state)

	2010	2020	2030	2040	2050
DOE-US					
Complete Price Scenario	0.91	-1.29	-6.02	-10.23	-12.21
Due to crude oil prices changes alone	0.77	-2.02	-6.26	-9.80	-11.53
Due to coal prices changes alone	0.09	0.51	0.16	-0.42	-0.59
Due to natural gas prices changes alone	0.05	0.28	0.09	-0.02	-0.08
IEA_OECD					
Complete Price Scenario	2.44	2.43	-2.64	-4.96	-7.24
Due to crude oil prices changes alone	1.16	-0.48	-4.64	-6.56	-8.46
Due to coal prices changes alone	1.22	2.72	1.69	1.31	0.91
Due to natural gas prices changes alone	0.04	0.00	0.08	0.07	0.12
IHS					
Complete Price Scenario	2.50	12.15	13.84	13.65	14.70
Due to crude oil prices changes alone	1.05	6.06	7.95	7.80	8.95
Due to coal prices changes alone	1.47	6.15	5.96	5.88	5.77
Due to natural gas prices changes alone	-0.01	0.04	0.09	0.13	0.16

which prices decrease. The emissions intensity reaches 0.3933 kt CO_2 per 1000 Euros of GDP in the IHS scenario, 0.3592 kt CO_2 per 1000 Euros of GDP in the IEA-OECD and 0.3462 kt CO_2 per 1000 Euros of GDP in the DOE-US. At the steady state, the decrease in the emissions intensity is more pronounced in the DOE-US scenario than in the IEA-OECD.

4.3. Climate Policy Implications

Fuel prices, through their impact on emissions growth, have important implications for the level of policy intervention required to achieve a particular emissions target and to the expected costs of a particular target. The former is important in the design of a package of policy instruments capable of achieving climate policy objectives while the latter affects the strength of domestic targets. The effects of the different fuel price scenarios on the state of compliance with the Kyoto protocol and EU 2020 emissions targets are presented in Table 10.

Table 10: The Impact of Fossil Fuel Price Scenarios on Climate Policy Targets

(Mt CO_2)

	2008-2012	2018-2022
	Kyoto	**EU 20/20**
Targets **[Carbon Dioxide Emissions from Fossil Fuel Combustion Activities Only]**	54.1	62.8
Model Benchmark Carbon Dioxide Emissions	60.4	71.9
Model Counterfactual Carbon Dioxide Emissions		
DOE-US	60.9	71.0
IEA-OECD	61.8	73.6
IHS Global Insight	61.9	80.6
Influence of Fossil Fuel Prices		
	Compliance Deficit	
Model Benchmark Compliance Deficit	6.3	9.1
Model Counterfactual Compliance Deficit		
DOE-US	6.8	8.2
IEA-OECD	7.8	10.9
IHS Global Insight	7.8	17.8
	Percent Change	
DOE-US	8.77	-10.20
IEA-OECD	23.38	19.18
IHS Global Insight	24.01	95.90

According to our baseline results, the benchmark compliance deficit for the Kyoto Protocol in Portugal is an average of 6.3 Mt CO_2 per year between 2008 and 2012. Now, all of our different price scenarios consider a short term reduction in fuel prices. Accordingly, we simulate greater levels of emissions growth for the Kyoto compliance period than if the current price level persists. Simulations results suggest that the actual compliance deficit grows to 6.8 Mt CO_2 in the DOE-US scenario, 7.8 Mt CO_2 in the IEA-OECD scenario and in the IHS scenario, a 8.8%, 23.4% and 24.0% increase over the baseline deficit, respectively.

The EU 2020 targets take effect in a markedly different fuel price environment with marginally higher fuel prices in two of the three price scenarios, coupled with substantial differences in relative prices. As a result, the compliance deficit in 2020 falls from 9.1 Mt CO_2 in the benchmark scenario to 8.2 Mt CO_2 in the DOE-US scenario. In the IEA-OECD scenario, we observe an increase to 10.9 Mt CO_2 which reflects the growing reliance on coal. If low prices persist, as forecasted in the IHS scenario, the compliance deficit increases to 17.8 Mt CO_2.

This analysis allows us to naturally separate the reduction in emissions required to achieve the emissions targets into those attributable to energy market innovations and those that must rely on policy intervention. Energy market innovations account for 10.2% of the implied emissions reductions in the DOE-US scenario, an increase of 19.2% in the IEA-OECD scenarios and a 95.9% increase in the IHS scenario.

These concerns highlight the impact of fuel prices in the design of a package of policy instruments with the technical capacity for ensuring compliance with policy objectives. Indeed, the particular price scenario considered will be instrumental in defining the size of the policy package because the emissions reduction required by domestic policies depends critically on the evolution of fossil fuel prices. Furthermore, fuel prices are also important to our understanding of the feasibility and costs of different emissions targets. In environments in which higher fuel prices dominate, more ambitious targets than originally anticipated appear less costly on the margin. This facet of fuel price increases has been increasingly recognized by policy makers and, is one component of recent efforts to redefine climate policy objective in the European Union in 2020 and set long term emissions targets.

It could be argued, however, that the total reduction in emissions required to achieve a particular target should be separated into those reductions attributable to market price mechanisms and to public policy intervention. The costs of emissions reductions driven by price adjustments can be substantial, in particularly for an energy-importing country. As a result, fuel prices should not be considered a structural part of baseline emissions growth, but a component of the mechanisms leading to the reduction in emissions relative to steady state growth levels.

This means that it is critical to define baseline emissions that reflect steady state assumptions in which prices are constant and therefore measure the costs of fuel price changes and the supplemental policy efforts needed to achieve any given emissions target.

5. On the Economic and Budgetary Impact of Fossil Fuel Prices

We now focus on the economic and budgetary impacts of the different fossil fuel price scenarios. These results are presented in tables 11, 12, and 13. This is central to our quest to capture the energy-economy feedbacks in the identification of emissions patterns. It is also central to our contention that reductions in emissions due to fuel price changes have real economic costs that need to be taken into account when designing climate policies. Finally, it highlights the fact that fuel price changes also affect the economic environment in which climate policies are to be designed and implemented.

5.1. On the Economic Impact

The three fuel price scenarios suggest markedly different impacts on the composition of private input demand as well as on economic activity levels and economic growth, particularly when comparing those scenarios in which prices rise over the long term and those in which prices are forecast to fall. As the similarities between the economic and budgetary impacts of the DOE-US and IEA-OECD scenarios suggest, changes in the composite energy price, the firms' effective energy bill, are determinant in evaluating the extent to which operating costs will affect output. This is because, for the firm, specific energy sector adjustments, while important from an environmental perspective, are less important to the firms' output decisions than are the changes to the firms' energy bill. Indeed, by adjusting the composition of fuel demand, firms can limit the increase in energy costs to 1.5% in 2020 in both the DOE-US scenario and the IEA-OECD

Table 11: Economic and Budgetary Impact of the DOE-US Fossil Fuel Price Scenario

(Deviations from steady state baseline unless otherwise indicated)

		2010	2020	2030	2040	2050
Fossil Fuel Price Index		97.86	101.52	113.99	127.08	133.18
Macroeconomic						
Growth Rate		1.78	1.69	1.67	1.69	1.71
GDP		0.41	0.08	-0.73	-1.59	-2.23
Consumption		-1.31	-1.32	-1.33	-1.33	-1.33
Investment		0.33	-1.19	-2.48	-3.26	-3.74
Private Capital		0.07	-0.18	-1.03	-1.99	-2.76
Inv. Wind Energy		-11.17	-4.82	2.68	4.62	4.69
Labor Demand		0.76	0.58	0.13	-0.35	-0.67
Energy Imports		-0.81	2.12	9.65	16.43	19.27
Foreign Debt (percent of GDP)		104.42	85.95	68.66	56.88	50.48
Foreign Debt		-3.76	-20.78	-36.72	-47.58	-53.47
Public Sector						
Public Debt (percent of GDP)		84.21	77.46	71.46	67.51	65.40
Public Debt		-1.86	-9.71	-16.71	-21.32	-23.77
Total Expenditure		-2.94	-3.12	-3.20	-3.20	-3.21
	Public Consumption	-4.34	-4.27	-4.08	-3.89	-3.75
	Public Investment	-0.80	-2.25	-3.49	-4.24	-4.74
	Human Capital Inv.	-1.03	-1.15	-1.26	-1.36	-1.43
	Public Capital	-0.06	-0.45	-1.14	-1.92	-2.65
	Human Capital	-0.01	-0.06	-0.12	-0.17	-0.23
Total Tax		-0.19	-0.47	-1.10	-1.74	-2.17
	IRS	0.33	-0.38	-1.89	-3.40	-4.38
	IRC	0.52	0.67	-0.28	-1.52	-2.40
	VAT	-1.23	-1.46	-1.65	-1.76	-1.83
	SSC	0.45	0.03	-1.03	-2.13	-2.87

scenario, although by 2050 the differences in prices becomes more pronounced. Accordingly, in order to highlight differences between fuel price increases and decreases we first focus on the scenarios in which fuel prices increase, i.e., the DOE-US and IEA-OECD scenarios.

With higher fuel prices, larger expenditures on energy inputs have a negative impact on firms' net cash flow. Businesses reduce private investment by 1.2% and 3.7% in the DOE-US scenario and by 1.1% and 3.2% in the IEA-OECD scenario in 2020 and in 2050, respectively. This is consistent with the larger share of wind investment in the IEA-OECD scenario and a

Table 12: Economic and Budgetary Impact of the IEA-OECD Fossil Fuel Price Scenario

(Deviations from steady state baseline unless otherwise indicated)

		2010	2020	2030	2040	2050
Fossil Fuel Price Index		96.75	101.52	114.75	120.09	126.63
Macroeconomic						
Growth Rate		1.79	1.68	1.70	1.70	1.71
GDP		0.37	0.05	-0.68	-1.27	-1.85
Consumption		-1.09	-1.10	-1.10	-1.11	-1.11
Investment		0.36	-1.13	-1.98	-2.68	-3.18
Private Capital		0.07	-0.17	-0.90	-1.62	-2.29
Inv. Wind Energy		4.24	12.74	14.69	16.20	16.61
Labor Demand		0.65	0.48	0.05	-0.25	-0.55
Energy Imports		-1.36	1.66	9.23	12.28	15.55
Foreign Debt (percent of GDP)		105.10	88.92	75.16	65.21	59.27
Foreign Debt		-3.13	-18.04	-30.73	-39.90	-45.37
Public Sector						
Public Debt (percent of GDP)		84.45	78.55	73.73	70.32	68.33
Public Debt		-1.57	-8.45	-14.07	-18.04	-20.36
Total Expenditure		-2.47	-2.63	-2.66	-2.70	-2.71
	Public Consumption	-3.66	-3.59	-3.41	-3.29	-3.16
	Public Investment	-0.63	-1.97	-2.85	-3.55	-4.05
	Human Capital Inv.	-0.87	-0.97	-1.06	-1.14	-1.21
	Public Capital	-0.04	-0.38	-0.97	-1.60	-2.23
	Human Capital	-0.01	-0.05	-0.10	-0.15	-0.20
Total Tax		-0.14	-0.40	-0.99	-1.41	-1.81
	IRS	0.29	-0.33	-1.77	-2.76	-3.66
	IRC	0.44	0.60	-0.45	-1.14	-1.94
	VAT	-1.01	-1.23	-1.36	-1.46	-1.54
	SSC	0.42	0.00	-0.99	-1.69	-2.38

smaller share in the DOE-US scenario. The reduction in private investment levels drives down the stock of private capital which in turn has a negative impact on economic growth. The fact that the reduction in the stock of capital is smaller than the reduction in energy consumption suggests that with growing fuel prices firms substitute capital inputs for energy inputs. Over the long term, energy price increases have a negative impact on employment as well, despite short term employment gains in both the DOE-US and IEA-OECD scenarios. This is consistent with the substitution of labor inputs for energy inputs.

Given the impact of fuel prices on the private inputs (which as we will see next section is mirrored by reductions in public and human capital investment), it is no surprise that higher fuel prices have a negative impact on GDP. In 2050, in the DOE-US scenario GDP falls by 2.2% while in the IEA-OECD scenario GDP falls by 1.9%. Short term reductions in fossil fuel prices stimulate economic activity early in the model horizon, increasing GDP by close to 0.1% in 2020 in both the DOE-US scenario and the IEA-OECD scenario.

The feedback between domestic demand, production and income defines the impact of fuel prices on private consumption. The net effect of this process is a reduction in private consumption of 1.3% in the DOE-US scenario and 1.1% in the IEA-OECD scenario. Consumption smoothing behavior by households implies that these reductions are relatively constant throughout the model horizon.

The net effect of fuel price increases on the trade balance depends on the response of non-energy demand. Expenditure on fossil fuels increases by 2.1% in the DOE-US scenario and 1.7% in the IEA-OECD in 2020 and up to 19.3% and 15.6% in 2050, respectively which places positive pressure on the trade balance. This increase in fossil fuel expenditure, however, is offset by reductions in domestic final demand. As a result, the net effect of higher energy prices on foreign debt is negative. Although foreign debt as a fraction of the GDP falls, over the long term these remain at 50.5% in the DOE-US scenario and 59.3% in the IEA-OECD scenario.

The IHS scenario is particularly interesting because, in contrast to the two scenarios discussed above, fuel prices are projected to drop substantially. Accordingly, fossil energy inputs assume a larger role in production. The reduction in fuel prices stimulates an increase in private investment and labor, although at a lower rate of growth than that of energy inputs. Private investment increases by 1.6% and labor demand falls marginally. Naturally, the growth in input

Table 13: Economic Impact of the IHS Global Insight Fossil Fuel Price Scenario

(Deviations from steady state baseline unless otherwise indicated)

		2010	2020	2030	2040	2050
Fossil Fuel Price Index		95.63	82.04	78.84	79.32	77.68
Macroeconomic						
Growth Rate		1.84	1.82	1.78	1.79	1.78
GDP		-0.12	0.55	0.93	1.12	1.36
Consumption		0.98	0.98	0.98	0.98	0.98
Investment		1.02	1.62	1.64	1.89	2.11
Private Capital		0.14	0.76	1.21	1.48	1.75
Inv. Wind Energy		-10.69	-9.36	-7.94	-7.47	-7.21
Labor Demand		-0.44	-0.05	0.14	0.22	0.34
Energy Imports		-2.49	-9.97	-11.95	-11.40	-12.54
Foreign Debt (percent of GDP)		111.74	120.72	125.69	129.51	131.99
Foreign Debt		2.98	11.26	15.84	19.36	21.65
Public Sector						
Public Debt (percent of GDP)		86.91	89.93	91.57	92.81	93.54
Public Debt		1.29	4.81	6.73	8.17	9.02
Total Expenditure		2.08	2.05	2.01	2.03	2.03
	Public Consumption	2.90	2.72	2.63	2.60	2.54
	Public Investment	1.70	2.13	2.16	2.34	2.54
	Human Capital Inv.	0.60	0.65	0.69	0.73	0.77
	Public Capital	0.13	0.63	1.06	1.39	1.69
	Human Capital	0.01	0.03	0.06	0.09	0.12
Total Tax		0.25	0.78	1.06	1.17	1.33
	IRS	-0.33	0.94	1.67	1.94	2.29
	IRC	-0.60	0.46	1.13	1.28	1.59
	VAT	1.08	1.17	1.16	1.20	1.23
	SSC	-0.05	0.87	1.31	1.50	1.78

levels has a positive impact on production, increasing GDP by 0.6%. The positive effects on income increases private consumption expenditure by 1.0%. These demand increases, however, lead to an increase in foreign debt to 132.0% of GDP in 2050.

5.2. On the Budgetary Impact

The impact of fuel prices on activity levels affects the size of the tax bases and public sector tax receipts. Contracting tax bases in the DOE-US and IEA-OECD scenarios drive a 0.5% and 0.4% reduction in tax revenue. In contrast, economic growth stimulated by falling fossil fuel prices in the IHS scenario increases the tax bases and allows for a 0.8% increase in tax revenue.

The changes in total tax receipts are driven primarily by changes in VAT tax revenues, the largest source of public revenues. These changes in turn are directly related to the changes in private consumption, the largest component of its tax base. Simulation results suggest that the share of VAT revenue in total tax revenue falls in the DOE-US and IEA-OECD scenarios and increases in the IHS. The falling share of VAT receipts in the DOE-US and IEA-OECD scenarios is accompanied by increasing shares for social security contributions, reflective of the shift towards employment in production. In absolute terms, the reduction in revenues associated with fuel price increases is led by a reduction in VAT revenue of 1.5% in the DOE-US scenario and 1.2% in the IEA-OECD scenarios. In the IHS scenario, VAT revenue increases by 1.2%.

On the expenditure side, the public sector optimally adjusts its spending patterns in response to fuel price variations. In both the DOE-US and IEA-OECD scenarios, net expenditures fall, coupled with a shift in spending from public consumption to public investment activities. Total public expenditure falls by 3.1% and 2.6% in the DOE-US and IEA-OECD scenarios while public consumption falls by 4.3% and 3.6%, respectively. In the IHS scenario, public expenditure increases by 2.0% and public consumption by 2.7%.

The shift in public spending patterns has an important impact on economic growth. This is because the public sector has a direct impact on production through investment in education and in public capital. Public capital investment drops by 2.3% in the DOE-US scenario and by 2.0% in the IEA-OECD scenarios while public investment in human capital falls by 1.2% and 1.0%, respectively. The larger drop in human capital investment, however, corresponds to smaller losses to the stock of human capital due to the size of the stock, and its depreciation rate. Overall, the firms' input structure shifts towards a greater utilization of human capital in production relative to public capital and a greater use of both relative to energy inputs. The reduction in public investment activities further reinforces the negative effect of decline in private inputs on production activities and has a negative impact on economic performance. In turn, public spending growth in the IHS price scenario is led by increases in investment in human capital and public capital, which lead to a higher growth pattern for the economy.

Despite tax revenue losses, the reduction in expenditure levels reduces public debt levels by 9.7% and 8.5% in the DOE-US and IEA-OECD scenarios. In the IHS price scenario, expenditures increase faster than tax revenue which results in an increase in public debt levels of 4.8%. This leads to public-debt to GDP ratios of 77.5% in the DOE-US scenario and 78.6% in the IEA-OECD scenario. The opposite is true with the IHS scenario where the public-debt to GDP ratio reaches 89.9%.

5.3. Implications for Economic and Budgetary Policy

Climate policies are not designed and implemented in a vacuum. They are framed by the economic and fiscal policy environments. Fuel prices, by affecting economic performance, directly affect the pursuit of policies to promote long term growth in general and convergence to EU standards of living in particular. Indeed, our results indicate that higher fuel prices have a negative effect on long-term growth, and likely, given the special vulnerabilities of Portugal as a small energy-importing economy, real convergence as well. Accordingly, they will tend to create a policy environment less conducive to the design and implementation of further climate policies that may also hurt economic growth.

In addition, fuel prices have a pronounced impact on the public sector and thereby important policy implications for the Portuguese government in the context of the Stability and Growth Programs in general and the current quest for fiscal consolidation in particular. Increasing fuel prices negatively impact economic performance and reduce tax revenues. In addition, the public sector optimally reduces investment activities. While this further compounds output losses, it alleviates pressure on the budget. Accordingly, higher fuel prices can contribute to reducing the public deficit at the expense of real convergence.

These considerations highlight the relevance of a meaningful modeling of the public sector. In the absent of changes in public expenditures, tax receipts fall by 1.0% and 0.8% by 2050 in the DOE-US and IEA-OECD scenarios, respectively and grow by 0.6% in the IHS scenario. These are substantially smaller magnitudes than those that occur once we account for changes in investment levels. In an environment of stable and exogenous public spending decisions any changes in tax revenues translate directly into changes in the public deficits. Accordingly, one would project a deterioration of the deficit due to higher prices while we actually project an improvement in the deficit and the longer term public debt to GDP position.

The general point is both methodological and conceptual. From a methodological perspective, if the feedback mechanism on public spending are ignored, any budgetary projections are liable to seriously misrepresent the effects of higher fuel prices, namely that higher fuel prices may actually improve the budgetary situation. From a conceptual perspective, if fuel price changes are perceived to negatively affect the public budget, they create a less conducive environment for climate policies that may require tax expenditures for example.

6. Sensitivity Analysis and Methodological Implications

6.1. Sensitivity Analysis with respect to the Model Structure

Endogenous growth and endogenous public sector behavior are key features of our model. Table 14 presents the sensitivity of our results to these aspects of the model. The absence of endogenous growth coupled with exogenous public sector behavior greatly affects the

Table 14 Sensitivity Analysis with respect to the Model Structure

(percent deviation from baseline in 2050)

	GDP	Tax Revenue	Public Debt	Energy	Carbon Dioxide Emissions
			DOE-US		
Central Modeling Assumptions	-2.23	-2.17	-23.77	-10.44	-12.21
Exogenous Public Consumption (1)	-1.74	-1.63	8.30	-9.98	-11.77
Exogenous Labor (2)	-1.54	-1.62	-13.10	-9.81	-11.59
Exogenous Growth (3)	-1.16	-1.36	-15.74	-9.46	-11.25
Exogenous Public Sector (1) + (2) + (3)	-0.86	-0.98	14.25	-9.19	-10.98
			IEA-OECD		
Central Modeling Assumptions	-1.85	-1.81	-20.36	-5.90	-7.24
Exogenous Public Consumption (1)	-1.44	-1.35	6.63	-5.50	-6.85
Exogenous Labor (2)	-1.28	-1.34	-11.22	-5.35	-6.69
Exogenous Growth (3)	-0.95	-1.12	-13.62	-5.04	-6.39
Exogenous Public Sector (1) + (2) + (3)	-0.71	-0.81	11.59	-4.81	-6.16
			IHS Global Insight		
Central Modeling Assumptions	1.36	1.33	9.02	10.70	14.70
Exogenous Public Consumption (1)	1.04	0.97	-11.90	10.35	14.34
Exogenous Labor (2)	1.00	1.04	4.82	10.31	14.30
Exogenous Growth (3)	0.70	0.82	4.44	9.99	13.95
Exogenous Public Sector (1) + (2) + (3)	0.56	0.59	-15.54	9.83	13.79

evaluation of the impact of fuel prices. Exogenous growth implies higher levels of investment spending when fuel prices are projected to increase. This results in substantially smaller output losses and therefore substantially smaller reduction in emissions levels. Naturally, tax revenues decline by a lower amount but, with exogenous public spending, result in higher deficits, particularly pronounced for an exogenous consumption trajectory. Therefore, ignoring long-term growth effects would lead to a serious misrepresentation of the effects on fuel prices on carbon emissions, economic activity, and the public budget.

6.2. Sensitivity Analysis with respect to the Elasticities of Substitution

It can be shown that the elasticity of substitution among energy inputs and between energy and value added can generate continuous approximations which are consistent with

Table 15 Sensitivity Analysis with respect to the Elasticities of Substitution

(percent deviation from baseline in 2050)

Elasticity of Substitution	GDP	Tax Revenue	Public Debt	Energy	Carbon Dioxide Emissions
Elasticity of Substitution between Value Added and Energy					
DOE-US					
0.1	-2.04	-2.28	-25.10	-2.01	-3.82
0.4	-2.23	-2.17	-23.77	-10.44	-12.21
1.0	-2.59	-1.96	-21.18	-26.29	-27.97
IEA-OECD					
0.1	-1.68	-1.88	-21.31	1.47	0.14
0.4	-1.85	-1.81	-20.36	-5.90	-7.24
1.0	-2.18	-1.66	-18.47	-20.09	-21.43
IHS Global Insight					
0.1	1.13	1.28	8.62	3.36	7.05
0.4	1.36	1.33	9.02	10.70	14.70
1.0	1.92	1.44	10.00	28.64	33.37

Elasticity of Substitution	GDP	Tax Revenue	Public Debt	Energy	Carbon Dioxide Emissions
Elasticity of Substitution between crude oil and other energy sources					
DOE-US					
0.1	-2.25	-2.19	-23.95	-12.37	-13.38
0.4	-2.23	-2.17	-23.77	-10.44	-12.21
1.0	-2.19	-2.13	-23.36	-5.89	-9.45
IEA-OECD					
0.1	-1.85	-1.81	-20.37	-6.17	-7.41
0.4	-1.85	-1.81	-20.36	-5.90	-7.24
1.0	-1.85	-1.81	-20.34	-5.32	-6.87
IHS Global Insight					
0.1	1.36	1.32	9.01	11.44	15.16
0.4	1.36	1.33	9.02	10.70	14.70
1.0	1.37	1.33	9.05	9.15	13.73

energy systems data from engineering estimates [Gerlagh et al. (2002) and Kiuila and Rutherford (2010)]. This parameter can be used to approximate the availability of low carbon alternatives and the degree to which new capital equipment reduces energy consumption through efficiency.

Table 15 presents the impact on the model results of different assumptions about the elasticities of substitution. We find that the elasticity of substitution between value added and energy plays a significant role and, in particular, a significantly larger role on the impact of fuel prices than does the elasticity of substitution between crude oil and other types of energy [see Jacoby et al. (2006), Wissema and Dellink (2007), and Schubert and Turnovsky (2010)].

The greater relative importance of the elasticity of substitution between value added and energy on energy consumption and emissions highlights the importance of considering economic feedbacks in climate policy analysis. More importantly, we find that the order of magnitude of the changes in the economic and budgetary results due to differences in the elasticities of substitution – a widely understood effect – pale in comparison with the changes generated by the endogenous growth mechanisms and endogenous public sector behavior – effects largely ignored in the literature. In contrast, the elasticity of substitution parameters play a larger role in defining the impact of fuel prices on energy consumption and on emissions. These effects are driven by the relative roles of income and substitution effects in defining the impact of fuel prices.

7. Summary and Concluding Remarks

In this paper, we examine the environmental, economic and budgetary impacts of fuel prices using a dynamic general equilibrium model of the Portuguese economy which highlights the mechanisms of endogenous growth and includes a detailed modeling of the public sector. High fuel prices under the DOE-US and the IEA-OECD scenarios increase operating costs, reduce energy consumption, employment and private investment, while shifting the input mix towards labor and capital. In contrast, in the IHS scenario, in which fuel prices are projected to drop, the changes to the input structure favor energy inputs. These changes lead to a long term drop of 2.2% in GDP by 2050 in the DOE-US scenario and of 1.9% in the IEA-OECD scenario and an increase of 1.4% in the IHS scenario.

Higher fuel prices have an important impact on the public sector account and public investment activities. A contracting tax base reduces tax revenues, led by reductions in VAT revenues, while a reduction in public spending, and public investment in particular, further compounds the long-term output and employment losses. These are, however, consistent with a shrinking public sector leading to reduction in public sector deficits and lower public debt to GDP levels. Thus, while ameliorating the situation for public finances, these adjustments negatively affect policy efforts to encourage convergence with EU standards.

Fossil fuel prices are important drivers of emissions growth due to their impact on the energy sector and on economic growth. Our results suggest that in absolute terms emissions in 2020 would be 1.3% lower in the DOE-US scenario and 2.4% greater in the IEA-OECD scenario relative to the steady state emissions projection. Over the long term, beyond 2020, however, as fuel prices grow, emissions fall in both scenarios relative to the steady state. Under the IHS scenario we would see an increase in emissions of 12.2% by 2020 relative to the steady state emissions. On the other hand and in relative terms under the current emission targets for 2020, higher fuel prices in the DOE-US scenario account for 10.2% of the implicit emissions deficit, while relative price changes led by lower prices for coal result in a 19.2% increase of the implied emissions deficit for the IEA-OECD scenario. Under the IHS scenario, declining fuel prices would increase the emissions deficit by 95.9%.

Our results highlight the importance, for policy analysis, of accounting for the dynamic feedbacks between energy demand and the economy. The striking similarities in economic and budgetary effects observed for the DOE-US and IEA-OECD scenarios, coupled with the dramatically different energy and environmental effects in these two scenarios, highlights the importance of relative fuel prices for environmental accounts, while the net effect of price changes on total energy costs is fundamental in determining the impact on economic and public accounts. Furthermore, the endogenous growth mechanisms play an important role in understanding the impact of fuel prices. Specifically, tax revenue losses reduce the resources available for productive public sector activities. This affects the level of economic activity, energy demand and, as a result, emissions growth. Exogenous economic growth assumptions result in substantially smaller GDP losses in the presence of higher fuel prices, resulting in larger baseline emissions growth scenarios.

In putting these feedback effects in context, it is useful to compare our results with the projections of the Portuguese Environmental Agency (APA). Portuguese energy sector emissions, with existing policy measures in place, are forecasted to grow to 69.3 Mt CO_2 in 2020 (Agência Portuguesa do Ambiente, 2010). This is 6.3% lower than the emissions level determined in our analysis using the IEA-OECD price scenario. The point is that ignoring the dynamic feedbacks of fuel prices with economic performance may lead to a serious misspecification of the actual baseline emission scenarios used to formulate policies. Accordingly, policy instruments and programs for reducing emissions must be flexible and adjust to the economic environment. In the case of Portugal our results suggest that the efforts for compliance with 2020 emissions targets are set to overshoot their mark in one of the three scenarios and undershoot in the other two. While overshooting the target may not be an undesirable outcome for environmental reasons, it comes at a price in terms of its impact on economic performance as we highlight.

The results in this paper, as important as they may be for the Portuguese case, have much more general policy implications. In the EU, the expected direct energy system costs computed today for the 2020 targets are 30% lower than that calculated two years ago [see, for example, EU (2010a)]. This reduction is due, aside from the ongoing recession, to an increase in projected oil prices in 2020, and the implied changes in the baseline emissions growth scenario. As a consequence there is the idea that the 2020 targets should be redefined in a stricter manner. Our results suggest that this may be a rather misleading conclusion in that it fails to account for the economic costs associated with the expected increase in fuel prices. While the direct costs of the climate policy package itself may be lower because a smaller portion of the emissions target remains outstanding, overall, the cost of the emissions target grows because the market forces driving a reduction in emissions relative to steady state come at a substantial economic cost.

As corollary, it is important to define baseline emissions growth with reference to steady state economic growth with constant fuel prices. Thus, the total reduction in emissions can be decomposed into the impact of market forces and of policy efforts. By defining the baseline in these terms, cost comparisons across countries become more meaningful. Indeed, in making comparisons across countries, it is fundamental for both efficiency and equity reasons to consider how fuel prices affect economic activity, in addition to their role in defining emissions levels. Accordingly, this definition can greatly increase transparency and clarity in international negotiations and in the establishment of emissions targets.

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