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E-QUEST – A Multi-Region Sectoral Dynamic General Equilibrium Model with Energy

Model Description & Applications to Reach the EU Climate Targets

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Abstract

This paper describes a micro-founded, fully forward-looking dynamic general equilibrium (DGE) model with energy sectors that is used to analyse the macroeconomic impact of climate mitigation policy in the European Union (EU). The paper presents simulation results for the transitional costs of moving towards a net zero emissions economy. It does not attempt to assess the effects on growth of the green investments envisaged in the framework of the European Green Deal or the Recovery and Resilience Facility. Our model allows for substitutability between fossil fuels and clean energy inputs and considers different recycling options for the revenues collected by carbon taxes. We find that the costs of moving towards a net zero emissions economy can be significantly reduced when carbon taxes are used and are recycled to reduce other distortive taxes, or for subsidising clean energy.

JEL Classification: D5, Q43, Q50.

Keywords: climate change, sectoral DSGE, energy taxation, carbon taxes.

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CONTENTS

1. INTRODUCTION

Designing policies for climate change mitigation is one of the principal goals of the European Union beyond 2020. The aim of the European Green Deal is to make Europe the world's first climate-neutral continent by 2050 (European Commission, 2019). It is a very ambitious package of measures that should enable European citizens and businesses to benefit from a sustainable and inclusive green transition. The question is how this transition to a greenhouse gas-free economy can best be achieved. With current production structures dependent on carbon-based technologies, the challenge is to achieve a switch to decarbonised alternatives at minimum costs. This will require large-scale policy interventions, via a mixture of regulation, incentives and government-supported research and development.

Economic theory suggests carbon pricing as a central and efficient strategy to reduce carbon emissions and tackling climate change (Bovenberg and Goulder, 2002). Taxing carbon emissions, like auctioning ETS allowances, also yields revenues that can be recycled, either across the board to all taxpayers, or targeted to compensate industries or individuals that are losing most from a carbon tax. In the EU countries, a number of instruments help to curb greenhouse gas emissions. The EU introduced the emission trading system (ETS) for greenhouse gases (GHG) in 2005 and several Member States use carbon taxes as well. However, the EU also relies on regulation and emission standards to reduce GHG emissions. The latter are argued to have higher societal acceptability on equity grounds but compare unfavourably to carbon pricing on efficiency grounds. In order to garner greater political acceptability for carbon pricing it is therefore important to explicitly show the benefits from revenue recycling (Klenert et al, 2018).

Standard dynamic stochastic general equilibrium (DSGE) models lack the necessary details to make a direct link between climate policy efforts and their economic outcomes. In this paper, we set up a fully forward-looking dynamic general equilibrium model that is sufficiently detailed to address the main reform areas that are discussed within the EU's climate change strategy. The model's structure reflects the analytical requirements to assess various climate policy scenarios. We aim to capture the transmission mechanism of climate mitigation efforts via three main structural elements. First, starting from the sectoral disaggregation, we distinguish between "dirty", or greenhouse gas (GHG) emitting, and "clean", non-polluting energy sources and use. Second, we account for cutting GHG emissions through carbon taxes or emission restrictions imposed by the government. Third, we also account for the fact that fossil fuels, the main sources of GHG emissions, are exhaustible resources.

We illustrate the model properties in a couple of main climate policy scenarios discussed in the literature. Focusing on the long run, we compare different scenarios that all reduce net GHG emissions close to zero by 2050 but with different recycling schemes for the additional carbon tax revenue. We also perform additional sensitivity analyses to see how the underlying parameter assumptions influence the expected range of results. A key conclusion of our paper is that carbon taxes outperform the scenario based on pure regulations and our results support the weak form of double dividend as defined by Goulder (1995)[1], i.e. recycling the revenues by reducing any of the distortionary taxes can improve the GDP, consumption or employment effect relative to our lump-sum recycling scenario. In line with Freire-González (2017), who provides a comprehensive review of the literature, analysing 69 different simulations from 40 studies, we find that the strong form of double dividend is much harder to achieve, although when revenue is used to reduce distortive taxes or subsidise clean energy, the negative effects on GDP and consumption can be reduced significantly. In terms of their employment

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[1] Goulder (1995) distinguishes between the strong and weak form of the double dividend. The weak form of the double-dividend hypothesis states that recycling environmental tax revenues through lowering distortionary taxes results in cost savings relative to the case where revenues are returned via lump-sum transfers. The strong form of the double dividend asserts that an environmental tax reform increases not only environmental quality but also non-environmental welfare.

effects, the policies perform somewhat better, in particular targeted labour tax reductions. A sensitivity analysis shows these results crucially depend on the assumed substitution elasticity between clean and dirty energy and our assumptions on autonomous energy efficiency improvement[2] and learning by doing. While our specification is in line with the literature, and, if anything, on the conservative side, there remains considerable uncertainty about these factors. [3]

Acemoglu et al. (2012) show that in a model with endogenous and directed technical change the optimal policy involves both carbon taxes and research subsidies, so that excessively severe carbon taxes can be avoided. Sustainable growth can be achieved using temporary research subsidies to the clean sector when inputs are sufficiently substitutable. Our model supports this policy direction, and the scenario in which carbon tax revenues are recycled through subsidies to clean sectors yields the lowest output and welfare loses.

This paper is structured as follows. Section 2 contains a detailed description of the model. Section 3 discusses calibration of structural parameters. Section 4 shows the properties of the model through various climate policy scenarios and the final section concludes the analysis.

2. THE MODEL

The model is based on the standard QUEST III model (Ratto et al. 2009, Burgert et al. 2020), but it extends it with a sectoral and energy-source disaggregation in a multi-region setting. The E-QUEST model in this paper is set-up for two-regions, the European Union (*EU*) and the rest of the world (*R*). In each region, the economy consists of households, firms, a monetary and a fiscal authority. Following the standard DSGE literature, households can be liquidity or non-liquidity constrained depending on their access to financial markets and they offer differentiated labour services to firms in three skill levels, low-, medium-, and high-skilled. In each region, firms produce differentiated goods and services for domestic and foreign markets. Production requires labour, general (non-energy) capital, a composite of intermediate goods and a composite of “dirty” and “clean” capital-energy bundle. The main change in the E-QUEST model compared to the standard QUEST model is the inclusion of energy-input substitution allowing for a more detailed description of substitution possibilities in different energy sources for the economic agents. [4] Firms have (limited) substitution possibilities between "dirty" and "clean" capital-energy bundles. In the "dirty" capital-energy bundle, capital is combined with fossil fuel energy while in the "clean" bundle electricity is required to use the corresponding capital.

The model also differs from standard DSGE models by introducing *sectoral disaggregation* in order to address climate policy related measures targeting dirty and clean sectors. We distinguish seven sectors

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[2] The climate policy modelling literature uses this term for energy intensity improvements which are not related to changes in energy prices (Webster et al. 2008).

[3] Note that we focus here on budgetary-neutral policies to reach the net zero emission target through regulation or carbon taxes, and we disregard possible growth effects of a green investment action plan, as promoted by the European Union’s Green Deal.

[4] The present model differs in several respects from Conte, Labat, Varga and Zarnic (2010). That model had a similar core structure but added endogenous technological change. In contrast, here we introduce learning by doing and autonomous energy efficiency improvements to account for technological change. The production nesting is another main difference between the two models. While in the former model, energy is used as an intermediate input separate from an aggregate tangible capital composite, in our model we distinguish between two types of capital depending on their need for dirty or clean form of energy in order to operate. The distinction between dirty and clean capital-energy capacity enables us to better capture the substitution possibilities between the different energy sources.

in the model: two energy provider sectors, three tangible capital producing sectors and the rest of the economic activities are allocated into two sectors depending on their emission intensity. More specifically, there is a sector which extracts and provides the economy with *fossil fuels (F)* and another energy provider sector producing *electricity (E)* from clean (renewable) or dirty sources. Two of the tangible capital types require either fossil fuel or electricity to operate, each produced separately by a *fossil fuel-intensive (dirty) capital* manufacturing sector *(D)* and an *electricity-intensive (clean) capital* manufacturing sector. The third tangible capital producing sector manufactures *general, non-energy related capital* (*G*). As for the remaining economic activities, an *emission intensive sector (T)* is separated from the *rest of the sectors (RS)*. The rationale for separating an emission intensive sector is to examine the consequences of extending the burden of emission reductions from energy producing sectors to other non-energy producing sectors with high greenhouse gas emission potential. We distinguish two main sources of GHG emissions: emissions linked to the burning of fossil fuel and other GHG emissions (CO2 emissions from industrial processes and non-CO2 emissions). While the former type of emissions appear in all segments of our model-economies, the latter one is allocated to the emission intensive sector.[5] Emission abatement technologies in the model address these two types of emissions in a targeted manner. Emissions linked to the burning of fossil fuel can be abated by substituting away from the fossil fuels towards clean electricity, capital or intermediates while other GHG emissions can be mitigated by taking up additional abatement costs.[6]

As a dynamic general equilibrium model with sectoral disaggregation, our model builds on the DSGE approach to climate and energy related policy questions (see e.g. Heutel 2012, Golosov et al. 2014 and Annicchiarico and Di Dio 2015) while it also enables us to exploit the main sectoral interlinkages. Although our model has much less sectoral detail and regional disaggregation compared to the well-established, large-scale CGE models in the field (see e.g. Capros et al. 2013, Weitzel et al. 2019), it is sufficiently detailed to provide useful insights into the main transmission mechanism of climate mitigation policies. On the other hand, building on the DSGE approach has a number of advantages. The model features fully forward-looking intertemporal optimisation which is missing from the widely used static or recursive-dynamic CGE models.[7] While most CGE models rely on perfect competition, DSGE models employ imperfect (monopolistic) competition with real and nominal frictions in the markets for goods and labour services. Endogenous labour supply and demand with endogenous wage setting are also standard in DSGE models without the restrictive closure rules of CGE models.

We calibrate the model on the latest World Input-Output Database (WIOD www.wiod.org) with the following sectoral assumptions (see the Annex for the corresponding sectoral mapping). There are three investment good producing sectors, *G, D* and *C*: these sectors produce and sell general capital, dirty and clean capital goods to domestic and foreign firms, households and governments. Consumers and investors of these goods need fossil fuels or electricity respectively in order to use them. In each region, firms in the fossil fuel sector (*F*) extract and process fossil fuel, which is modelled as an exhaustible natural resource, for domestic and foreign distribution. Firms producing and distributing electricity in sector (*E*) are also subject to GHG emission limits depending on their reliance on fossil fuels for electricity production. Finally, other non-energy sectors are grouped into two sectors, an emission intensive sector (*T*) which compromises sectors with high GHG emission potential like steel

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[5] Note that we do not model carbon sinks.

[6] The emission intensive sector includes the subsectors of different energy intensive industries, e.g. steel, cement, pulp and paper production, transport and also agriculture. Although each of these sectors face different emission abatement technologies, the modelling of these goes beyond the scope of our paper. Our emission abatement technology is an aggregate representation of abatement efforts for these groups of sectors. Consequently, in the simulations we cannot trace specifically the different components of non-energy related emissions from these sectors, only their aggregate levels. For an advanced treatment of abatement options see Weitzel et al. (2019).

[7] Forward-looking optimisation allows for a more rigorous modelling of investments in physical and financial assets and the domestic and foreign debt accumulation. This feature also allows for the inclusion of comprehensive monetary and fiscal policy rules together with forward-looking interest parity conditions for modelling the price, interest rate and foreign exchange rate dynamics.

production, transport, agriculture, and an aggregate of the remaining sectors (RS). These latter sectors sell consumption and intermediate inputs to domestic and foreign private households, firms and governments.

The fiscal authority receives its revenue from taxes on domestic and imported goods and taxes on factor incomes. On the expenditure side, we assume that government consumption, government transfers and government investment are proportional to GDP and unemployment benefits are indexed to wages. There is a monetary and a fiscal authority in each region. The monetary authority follows a standard Taylor-rule. In the following model-description we omit the country indices and use them only to describe the bilateral sectoral trade between the regions.

2.1. HOUSEHOLDS

The household sector consists of a continuum of households $h \in [0,1]$. A share ς of these households is not liquidity constrained (Ricardian) and indexed by r. They have access to financial markets where they can buy and sell domestic assets (government bonds), and accumulate physical capital, which they rent out to the firms. The remaining share of households is liquidity constrained and indexed by l. These households cannot trade in financial and physical assets and consume their disposable income each period. We assume that both households offer low-, medium-, and high-skilled labour services. In each skill group, households supply differentiated labour services to unions, which act as wage setters in monopolistically competitive labour markets.[8] The unions pool wage income and distribute it in equal proportions among their members.

The period utility function is identical for both household types. Their utility function is separable in consumption (C_t) and leisure $(1 - NPART_{skill,t} - L_{skill,t})$, where $L_{skill,t}$ and $NPART_{skill,t}$ are the employment and non-participants rates in the labour force by skill levels (*L-low*, *M-medium*, *H-high skilled*). We also allow for habit persistence in consumption (h^c). Period utility is determined as:

$$U(C_{L,t}, L_{L,t}) = (1-h)log\left(C_{L,t} - h^c \bar{C}_{L,t-1}\right) + \sum_{skill \in \{L,M,H\}} \omega_{skill} \frac{(1-NPART_{skill,t}-L_{skill,t})^{1-\kappa_{skill}}}{1-\kappa_{skill}} \quad (1)$$

for the liquidity constrained, and

$$U(C_{r,t}, L_{L,t}, L_{H,t}) = (1-h)log\left(C_{r,t} - h^c \bar{C}_{r,t-1}\right) + \sum_{skill \in \{L,M,H\}} \omega_{skill} \frac{(1-NPART_{skill,t}-L_{skill,t})^{1-\kappa_{skill}}}{1-\kappa_{skill}} \quad (2)$$

for Ricardians, where κ_{skill} >0, is a labour supply elasticity parameter. We assume CES preferences with common elasticity but a skill specific weight (ω_{skill}) on leisure. This is necessary in order to capture differences in employment levels across skill groups. Households consume a bundle of domestic and imported goods and services produced by each sector (*E, F, C, G, D, T, RS*) according to the following CES aggregate:

$$C_{h,t} = \left(\rho_{dur}{}^{\frac{1}{\sigma_C}} C_{DUR,h,t}^{\frac{\sigma_C - 1}{\sigma_C}} + (1-\rho_{dur})^{\frac{1}{\sigma_C}} C_{NDUR,h,t}^{\frac{\sigma_C - 1}{\sigma_C}} \right)^{\frac{\sigma_C}{\sigma_C - 1}} \quad (3)$$

where $C_{DUR,h,t}$ and $C_{NDUR,h,t}$ are the durable and non-durable bundles in consumption defined as

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[8] One can also define an alternative allocation of skills where liquidity constrained households can offer only low-skilled labour services while the not liquidity constrained supply only medium, and high-skilled services. However, this modification in the allocation of skills does not change the results significantly.

$$C_{DUR,h,t}=\left(\rho_{EN}{}^{\frac{1}{\sigma_{dur}}}C_{EN,h,t}^{\frac{\sigma_{dur}-1}{\sigma_{dur}}}+(1-\rho_{EN})^{\frac{1}{\sigma_{dur}}}C_{G,h,t}^{\frac{\sigma_{dur}-1}{\sigma_{dur}}}\right)^{\frac{\sigma_{dur}}{\sigma_{dur}-1}} \tag{4}$$

$$C_{NDUR,h,t}=\left(\rho_{T}{}^{\frac{1}{\sigma_{ct}}}C_{T,h,t}^{\frac{\sigma_{ct}-1}{\sigma_{ct}}}+(1-\rho_{T})^{\frac{1}{\sigma_{ct}}}C_{RS,h,t}^{\frac{\sigma_{ct}-1}{\sigma_{ct}}}\right)^{\frac{\sigma_{ct}}{\sigma_{ct}-1}} \tag{5}$$

In equation (4), durable goods, $C_{DUR,h,t}$ are the composite of an energy bundle $C_{EN,h,t}$ and the non-energy related G products. The energy bundle is again a CES aggregate of fuel and electricity intensive baskets, $C_{DF,h,t}$ and $C_{CE,r,t}$:

$$C_{EN,h,t}=\left(\rho_{DF}{}^{\frac{1}{\sigma_{cdc}}}C_{DF,h,t}^{\frac{\sigma_{cdc}-1}{\sigma_{cdc}}}+(1-\rho_{DF})^{\frac{1}{\sigma_{cdc}}}C_{CE,h,t}^{\frac{\sigma_{cdc}-1}{\sigma_{cdc}}}\right)^{\frac{\sigma_{cdc}}{\sigma_{cdc}-1}} \tag{6}$$

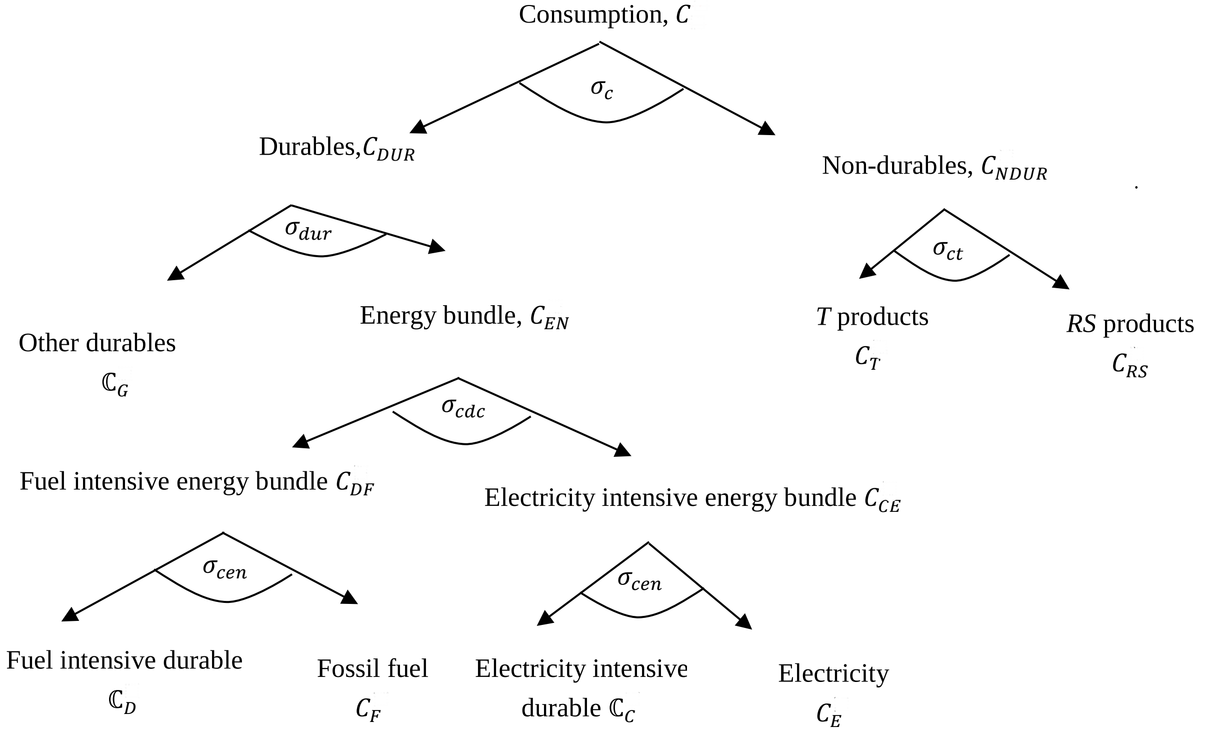
Note that of the ρ share parameters, and σ substitution elasticities, σ_{cdc} is of particular interest as this elasticity determines the substitution possibilities between the fossil fuel and electricity-intensive bundles. The corresponding energy bundles use fossil fuel (F) or electricity (E) respectively as

$$C_{DF,h,t}=\left(\rho_{D}{}^{\frac{1}{\sigma_{cen}}}C_{D,h,t}^{\frac{\sigma_{cen}-1}{\sigma_{cen}}}+(1-\rho_{D})^{\frac{1}{\sigma_{cen}}}C_{F,h,t}^{\frac{\sigma_{cen}-1}{\sigma_{cen}}}\right)^{\frac{\sigma_{cen}}{\sigma_{cen}-1}} \tag{7a}$$

$$C_{CE,h,t}=\left(\rho_{C}{}^{\frac{1}{\sigma_{cen}}}C_{C,h,t}^{\frac{\sigma_{cen}-1}{\sigma_{cen}}}+(1-\rho_{C})^{\frac{1}{\sigma_{cen}}}C_{E,h,t}^{\frac{\sigma_{cen}-1}{\sigma_{cen}}}\right)^{\frac{\sigma_{cen}}{\sigma_{cen}-1}} \tag{7b}$$

Figure 1 below illustrates the consumption bundle which is the same for both household types.

Figure 1. **The consumption nesting scheme in the E-QUEST model**



Durables

Note that durable goods ($\mathbb{C}_G$, $\mathbb{C}_D$ $\mathbb{C}_C$) in the household consumption basket stand for the stock of these goods with the following accumulation equations:

$$\mathbb{C}_{G,h,t} = C_{G,h,t} + (1-\delta_G)\mathbb{C}_{G,h,t-1}, \tag{8a}$$

$$\mathbb{C}_{D,h,t} = C_{D,h,t} + (1-\delta_D)\mathbb{C}_{D,h,t-1}, \tag{8b}$$

$$\mathbb{C}_{C,h,t} = C_{C,h,t} + (1-\delta_C)\mathbb{C}_{C,h,t-1}, \tag{8c}$$

where $C_{.,h,t}$ denote the current additional consumption of these goods and δ is the corresponding depreciation rate. We assume that households rent their durables from the RS sector for the same rental rate that the sectors pays on their corresponding capital.

2.1.1. Non-liquidity constrained households

Non-liquidity constrained households maximise an intertemporal utility function in consumption and leisure subject to a budget constraint. These households make decisions about consumption ($C_{r,t}$), and labour supply ($L_{z,t}$), the purchases of dirty and clean investment goods ($JD_{r,t}$, $JC_{r,t}$) and government bonds ($B_{r,t}$) and the renting of general, dirty and clean physical capital stocks ($KG_{r,t}$ $KD_{r,t}$, $KC_{r,t}$). They receive wage income ($W_{z,t}$), unemployment benefits[9] ($bW_{z,t}$), transfer income from the government ($TR_{z,t}$), and interest income (i_t, $i_{KD,t}$, $i_{KC,t}$).

Hence, non-liquidity constrained households face the following Lagrangian

$$\max_{\left\{\begin{matrix} C_{r,t},L_{r,L,t},L_{r,M,t},L_{r,H,t}B_{i,t} \\ JDr,t,JCr,t \\ KDr,t,KCr,t \end{matrix}\right\}_{t=0}^{\infty}} V_{r,0} = E_0 \sum_{t=0}^{\infty} \beta^t \left(U(C_{r,t}, L_{r,L,t}, L_{r,M,t}, L_{r,H,t})\right)$$

$$-E_0 \textstyle\sum_{t=0}^{\infty} \lambda_{r.t} \frac{\beta^t}{P_t} \left(\begin{array}{c} P_{C,t}C_{r,t} + B_{r,t} \\ +P_{IG,t}\left(JG_{r,t} + \Gamma_J(JG_{r,t})\right) \\ +P_{ID,t}\left(JD_{r,t} + \Gamma_{JD}(JD_{r,t})\right) + P_{IC,t}(JC_{r,t} + \Gamma_{JC}(JC_{r,t})) \\ -(1+i_{t-1})B_{i,t-1} \\ -\sum_{skill \in \{L,M,H\}} \left(\begin{array}{c} (1-t_{w,skill,t})s_{skill,t}W_{skill,t}L_{r,skil,t} \\ +bW_{skill,t}s_{skill,t}(1-NPART_{r,skill,t} - L_{r,skill,t}) \end{array}\right) \\ -(1-t_K)(i_{KG,t-1} - rp_{KG})P_{IG,t-1}KG_{r,t-1} - t_K\delta_{KG}P_{IG,t-1}KG_{r,t-1} \\ -(1-t_K)(i_{KD,t-1} - rp_{KD})P_{ID,t-1}KD_{r,t-1} - t_K\delta_{KD}P_{ID,t-1}KD_{r,t-1} \\ -(1-t_K)(i_{KC,t-1} - rp_{KC})P_{IC,t-1}KC_{r,t-1} - t_K\delta_{KC}P_{IC,t-1}KC_{r,t-1} \\ -TR_{r,t} - PR_{r,t} \end{array}\right) \tag{9}$$

$$-E_0 \sum_{t=0}^{\infty} \lambda_{r,t}\xi_{G,r,t}\beta^t\left(KG_{r,t} - JG_{r,t} - (1-\delta_{KG})KG_{r,t-1}\right)$$

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[9] Households only make a decision about the level of employment, but there is no distinction on the part of households between unemployment and non-participation. It is assumed that the government makes a decision how to classify the non-working part of the population into unemployed and non-participants. The non-participation rate (NPART) must therefore be seen as a policy variable characterising the generosity of the benefit system.

$$-E_0 \sum_{t=0}^{\infty} \lambda_{r,t} \xi_{D,r,t} \beta^t \left(KD_{r,t} - JD_{r,t} - (1-\delta_{KD}) KD_{r,t-1} \right)$$

$$-E_0 \sum_{t=0}^{\infty} \lambda_{r,t} \xi_{C,r,t} \beta^t \left(KC_{r,t} - JC_{r,t} - (1-\delta_{KC}) KC_{r,t-1} \right)$$

The budget constraints are written in real terms with the price for consumption and investments ($P_{C,t}$,$P_{IG,t}$, $P_{ID,t}$,$P_{IC,t}$) and nominal wages ($W_{skill,t}$) divided by GDP deflator (P_t). Note that the consumer price is the corresponding CES price aggregate of the consumption bundle and it also includes consumption taxes. Non-liquidity constrained households who share the total profit of all firms in the economy ($PR_{i,t}$) own all firms of the economy. As shown by the budget constraints, all households pay wage income taxes ($t_{w,z,t}$) and t_K capital income taxes less depreciation allowances ($t_K \delta_{KG}$, $t_K \delta_{KD}$ and $t_K \delta_{KC}$) after their earnings on tangible capital. When investing into capital the household requires premia rp_{KG}, rp_{KD} and rp_{KC} in order to cover the increased risk on the return related to these assets.

The investment decisions w.r.t. real capital are subject to convex adjustment costs as in Burgert et al. (2020), which are given by

$$\Gamma_{JX}(JX_{r,t}) = \frac{\gamma_{KX}}{2} \left(JX_{r,t} / KX_{i,t-1} - \delta_{KX} \right)^2 KX_{i,t-1} + \frac{\gamma_{IX}}{2} (\Delta JX_{r,t})^2 \qquad (10)$$

The adjustment cost function penalises the accelerations and decelerations in investment relative to the capital stock and in absolute terms. The first order conditions of the household with respect to consumption, financial and real assets are given by the following equations:

$$\frac{\partial W_0}{\partial C_{r,t}} => U_{C,r,t} - \lambda_{r,t} \frac{P_{C,t}}{P_t} = 0 \qquad (11a)$$

$$\frac{\partial W_0}{\partial B_{r,t}} => -\lambda_{r,t} + E_t \left(\lambda_{r,t+1} \beta (1+i_t) \frac{P_t}{P_{t+1}} \right) = 0 \qquad (11b)$$

$$\frac{\partial W_0}{\partial KG_{r,t}} =>$$

$$E_t \left(\lambda_{r,t+1} \frac{\beta P_{IG,t}}{P_{t+1}} \left((1-t_K)(i_{KG,t} - rp_{KG}) + t_K \delta_{KG} \right) \right) - \lambda_{r,t} \xi_{G,r,t} + E_t \left(\lambda_{r,t+1} \xi_{G,r,t+1} \beta (1-\delta_{KG}) \right) = 0 \qquad (11c)$$

$$\frac{\partial V_0}{\partial KD_{r,t}} =>$$

$$E_t \left(\lambda_{r.t+1} \frac{\beta P_{ID,t}}{P_{t+1}} \left((1-t_K)(i_{KD,t} - rp_{KD}) + t_K \delta_{KD} \right) \right) - \lambda_{r,t} \xi_{D,r,t} + E_t \left(\lambda_{r,t+1} \xi_{D,r,t+1} \beta (1-\delta_{KD}) \right) = 0 \qquad (11d)$$

$$\frac{\partial V_0}{\partial KC_{r,t}} =>$$

$$E_t \left(\lambda_{r.t+1} \frac{\beta P_{IC,t}}{P_{t+1}} \left((1-t_K)(i_{KC,t} - rp_{KC}) + t_K \delta_{KC} \right) \right) - \lambda_{r,t} \xi_{r,t} + E_t \left(\lambda_{r,t+1} \xi_{r,t+1} \beta (1-\delta_{KC}) \right) = 0 \qquad (11e)$$

2.1.2. Liquidity constrained households

Liquidity constrained households do not optimise intertemporally but simply consume their current income at each period. Real consumption of household k is thus determined by the net wage income plus benefits and net transfers:

$$P_{C,t}C_{L,t} = \sum_{skill\in\{L,M,H\}}\Big(\big(1-t_{w,skill,t}\big)s_{skill,t}W_{skill,t}L_{r,skil,t} + bW_{skill,t}s_{skill,t}(1-NPART_{r,skill,t} - L_{r,skill,t})\Big) + TR_{L,t}. \tag{12}$$

2.1.3. Wage setting

Within each skill group, a variety of labour services are supplied which are imperfect substitutes to each other. Thus, trade unions can charge a wage mark-up $(1/(1-1/\sigma_{skill}))$ over the reservation wage[10]. The reservation wage is given as the marginal utility of leisure divided by the corresponding marginal utility of consumption for liquidity and non-liquidity constrained households respectively (denoted by $U^{a}_{1-L,h,skill,t}$ and $U^{a}_{C,h,skill,t}$). The relevant net real wage to which the mark up adjusted reservation wage is equated is the gross wage adjusted for labour taxes, consumption taxes and unemployment benefits, which act as a subsidy to leisure. Our specification also allows for real wage inertia (ρ_w) following Blanchard and Gali (2007):

$$\left(\frac{U^{a}_{1-L,h,skill,t}}{U^{a}_{C,h,skill,t}}P_{C,t}\right)^{1-\rho_w}\left(\left(1-\frac{1}{\sigma_{skill}}\right)\left(1-t_{w,skill,t-1}-b\right)w_{skill,t-1}\right)^{\rho_w}$$

$$= \left(1-\frac{1}{\sigma_{skill}}\right)\left(1-t_{w,skill,t}-b\right)w_{skill,t} + \underbrace{\frac{\gamma_{w,skill}}{\sigma_{skill}}\left(w_{skill,t}\left(\pi_{w,skill,t}-\left(1-s_{fw}\right)\pi_{w,skill,t-1}\right) - \frac{w_{skill,t}}{(1+r_t)}\left(\pi_{w,skill,t+1}-\left(1-s_{fw}\right)\pi_{w,skill,t}\right)\right)}_{wage\ stickiness\ term}, \tag{13}$$

where b is the benefit replacement rate, π_w denotes the wage inflation, and γ_w is an adjustment cost parameter. Wage stickiness is captured via the s_{fw} parameter: the fraction 1-s_{fw} of workers ($0 \le s_{fw} \le 1$) forms expectations of future wage growth on the basis of wage inflation in the previous period.

2.2. FIRMS

Each firm produces a variety of the domestic good, which is an imperfect substitute for the varieties produced by other firms. Firms act as monopolistic competitors facing a demand function with a price elasticity given by $\sigma_{d,s}$, where s denotes the sectors (*E*, *F*, *C*, *D*, *G*, *T*, *RS*). Formally, sectoral output, $Y_{s,t}$ is a CES aggregate of $Y_{s,t}(j)$ varieties:

$$Y_{s,t} \equiv \left(\int_0^1 Y_{s,t}(j)^{\frac{\sigma_{d,s}-1}{\sigma_{d,s}}}\,dj\right)^{\frac{\sigma_{d,s}}{\sigma_{d,s}-1}} \tag{14}$$

and the demand function is given by

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[10] The mark-up depends on the intratemporal elasticity of substitution between differentiated labour services within each skill groups (σ_s) and fluctuations in the mark-up arise because of wage adjustment costs and the fact that a fraction (1-s_{fw}) of workers is indexing the growth rate of wages π_w to wage inflation in the previous period.

$$Y_{s,t}(j) = (P_{s,t}(j)/P_{s,t})^{-\sigma_{d,s}} Y_{s,t}. \tag{15}$$

Note that the elasticity value $\sigma_{d,s}$, implies sector-specific price mark-ups of $\tau_{d,s} = 1/(\sigma_{d,s} - 1)$.

The total production of each firm, $Y_{s,t}(j)$ is a CES of its value-added, $VA_{s,t}$ and the aggregate inputs from intermediate goods, $M_{s,t}$ according to

$$Y_{s,t}(j) = F\big(VA_{s,t}(j), M_{s,t}(j)\big) = A_s \left(sva_s^{\frac{1}{\sigma_{vam,s}}} VA_{s,t}(j)^{\frac{\sigma_{vam,s}-1}{\sigma_{vam,s}}} + sm_s^{\frac{1}{\sigma_{vam,s}}} M_{s,t}(j)^{\frac{\sigma_{vam,s}-1}{\sigma_{vam,s}}} \right)^{\frac{\sigma_{vam,s}}{\sigma_{vam,s}-1}} \tag{16}$$

where $\sigma_{vam,s}$ is the sectoral elasticity of substitution between the value added and the intermediates, and sva_s and sm_s are the corresponding weights. Value added is given by a Cobb-Douglas production function of general and energy-capital composite ($KGE_{s,t}$), labour input ($LCES_{s,t}(j)$) and it also includes exogenous technological progress, TFP_s :

$$VA_{s,t}(j) = \big(KGE_{s,t}(j)\big)^{\alpha_s} \Big(TFP_{s,t}\big(LCES_{s,t}(j) - FCL_s(j)\big)\Big)^{1-\alpha_s} KG_t^{\alpha_G} - TFP_{s,t}FCY_s(j) \tag{17}$$

with

$$LCES_{s,t}(j) = \left(\Lambda_L^{\frac{1}{\mu}} \big(\chi_L L_{L,s,t}\big)^{\frac{\mu-1}{\mu}} + \Lambda_M^{\frac{1}{\mu}} \big(\chi_M L_{M,s,t}\big)^{\frac{\mu-1}{\mu}} + \Lambda_H^{\frac{1}{\mu}} \big(\chi_H L_{H,s,t}\big)^{\frac{\mu-1}{\mu}} \right)^{\frac{\mu}{\mu-1}}, \tag{18}$$

$L_{L,t}$, $L_{M,t}$ and $L_{HY,t}$ denotes the employment of low, medium and high-skilled in final goods production respectively. Parameter Λ_{skill} is the corresponding share parameter (L, M, H), χ_{skill} is the efficiency unit, and μ is the elasticity of substitution between different labour types. Our formulation assumes that investment in public capital stock (K_G) increases total factor productivity with an exponent of α_G set to 0.10.

The use of non-energy related intermediate goods $\big(M_{s,t}\big)$ by sector s is a CES aggregate of intermediate consumption from all sectors (s'):

$$M_{s,t} = \left(\sum\nolimits_{s'} sm_{s',s}^{\frac{1}{\sigma_{Ms}}} M_{s',s,t}^{\frac{\sigma_{Ms}-1}{\sigma_{Ms}}} \right)^{\frac{\sigma_{Ms}}{\sigma_{Ms}-1}}, \tag{19}$$

where M_s is the total use of intermediate goods in sector s which is composed of intermediates produced by sectors s' ($M_{s',s}$). The corresponding share parameters are $sm_{s',s}$ while the elasticity of substitution is σ_{Ms}.

Capital use builds on general capital ($KGEC_{s,t}$) and a capital-energy composite ($KE_{s,t}$) according to the following CES aggregate with preference parameters $skge$ and ske, and $\sigma_{kge,s}$ elasticity of substitution:

$$KGE_{s,t}(j) = \left(skge_s^{\frac{1}{\sigma_{kge,s}}} \big(KGEC_{s,t}(j)\big)^{\frac{\sigma_{kge,s}-1}{\sigma_{kge,s}}} + ske_s^{\frac{1}{\sigma_{kge,s}}} \big(KE_{s,t}(j)\big)^{\frac{\sigma_{kge,s}-1}{\sigma_{kge,s}}} \right)^{\frac{\sigma_{kge,s}}{\sigma_{kge,s}-1}} \tag{20}$$

2.2.1. Capital-energy composite

In the capital-energy composite ($KE_{s,t}$), firms in each sector use dirty and clean capital-energy bundles, $KDE_{s,t}(j)$ and $KCE_{s,t}(j)$.

$$KE_{s,t}(j) = \left(skde_s^{\frac{1}{\sigma_{ke,s}}} \left(KDE_{s,t}(j)\right)^{\frac{\sigma_{ke,s}-1}{\sigma_{ke,s}}} + skce_s^{\frac{1}{\sigma_{ke,s}}} \left(KCE_{s,t}(j)\right)^{\frac{\sigma_{ke,s}-1}{\sigma_{ke,s}}} \right)^{\frac{\sigma_{ke,s}}{\sigma_{ke,s}-1}} \tag{21}$$

with preference parameters $skde_s$ and $skce_s$ and $\sigma_{ke,s}$ elasticity of substitution.

Within the dirty capital-energy bundle, firms use dirty capital ($KD_{s,t}$) which requires fossil fuel ($M_{F,s,t}$) to operate and clean capital ($KC_{s,t}$) which can be used with electricity ($M_{E,s,t}$) according to the following CES functions:

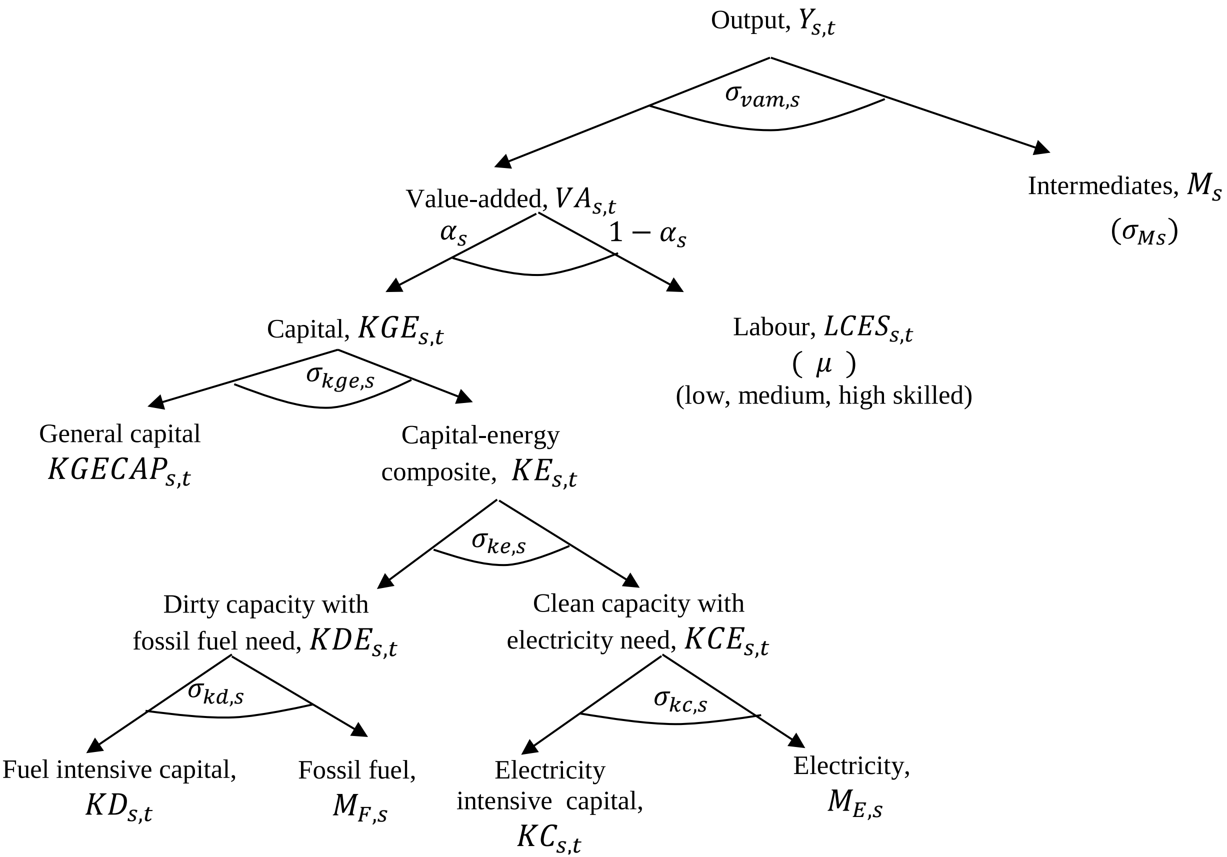
$$KDE_{s,t}(j) = \left(skd_s^{\frac{1}{\sigma_{kd,s}}} \left(u_{D,s,t}(j) \cdot KD_{s,t}(j)\right)^{\frac{\sigma_{kd,s}-1}{\sigma_{kd,s}}} + skfuel_s^{\frac{1}{\sigma_{kd,s}}} \left(ae_{F,s,t} M_{F,s,t}(j)\right)^{\frac{\sigma_{kd,s}-1}{\sigma_{kd,s}}} \right)^{\frac{\sigma_{kd,s}}{\sigma_{kd,s}-1}} \tag{22}$$

$$KCE_{s,t}(j) = \left(skc_s^{\frac{1}{\sigma_{kc,s}}} \left(u_{C,s,t}(j) \cdot KC_{s,t}(j)\right)^{\frac{\sigma_{kc,s}-1}{\sigma_{kc,s}}} + skelec_s^{\frac{1}{\sigma_{kc,s}}} \left(ae_{E,s,t} \cdot M_{E,s,t}(j)\right)^{\frac{\sigma_{kc,s}-1}{\sigma_{kc,s}}} \right)^{\frac{\sigma_{kc,s}}{\sigma_{kc,s}-1}} \tag{23}$$

where skX, $skfuel$ and $skelec$ are the preference parameters, $u_{X,s,t}$ and $\sigma_{kX,s}$, $X \in \{D, C\}$ are the capacity utilisation levels and substitution elasticities respectively while $ae_{F,s,t}$ and $ae_{E,s,t}$ can be used to capture energy efficiency improvements in the use of fossil fuel and electricity.

Figure 2 below shows the nested structure for production with the corresponding elasticities.

Figure 2. **The production nesting scheme in the E-QUEST model**



2.2.2. Profit maximisation

Real profit for firms can be written as total revenue less expenditure on intermediate consumption, labour compensation, rental cost of capital, adjustment cost and – if applicable – fees or taxes for CO_2 emission.

$$PR_{s,t}(j) = \frac{1}{P_t}\begin{pmatrix} P_{s,t}(j)Y_{s,t}(j) - \sum_{s'\in\left\{\substack{E,F\\T,RS}\right\}} PM_{s',s,t}M_{s',s,t}(j) - (1+ssc_t)\sum_{skill\in\{L,M,H\}} W_{skill,t}L_{skill,s,t}(j) \\ - i_{KG,t}PI_{G,s,t}KG_{s,t}(j) - i_{KD,t}PI_{D,s,t}KD_{s,t}(j) - i_{KC,t}PI_{C,s,t}KC_{s,t}(j) - \left(\Gamma^{P}_{s.t}(j) + \Gamma^{L}_{s.t}(j) + \Gamma^{u}_{s.t}(j)\right) \end{pmatrix} \tag{24}$$

where $PM_{s',s,t}$ and $M_{s',s,t}(j)$ are the price and the use of intermediate goods produced by sector *s'*, ssc_t is the employer social security contributions, $i_{KG,t}$ $i_{KD,t}$, $i_{KC,t}$, $PI_{G,s,t}$, $PI_{D,s,t}$ and $PI_{C,s,t}$ are the rental rates and prices of general, dirty and clean capital respectively.

The firms face technology constraints that restrict their capacity to adjust their inputs in the form of the following convex adjustment costs:

$$\Gamma^{P}_{s.t}(j) \equiv \frac{\gamma_P}{2}(\pi_{s,t}(j))^2 Y_{s,t}(j) \text{ where } \pi_{s,t}(j) \equiv P_{s,t}(j)/P_{s,t-1}(j) - 1 \tag{25}$$

$$\Gamma^{L}_{s.t}(j) \equiv \sum_{skill\in\{L,M,H\}} \frac{\gamma_{skill}}{2} W_{skill,t}\,(\Delta L_{s,skill,t}(j))^2 \tag{26}$$

$$\Gamma^{u}_{s.t}(j) \equiv (\gamma_{u1}\left(u_{D,s,t}(j) - 1\right) + \gamma_{u2}\left(u_{D,s,t}(j) - 1)^2\right)PI_{D,s,t}KD_{s,t}(j) + (\gamma_{u1}(u_{C,s,t}(j) - 1) + \gamma_{u2}(u_{C,s,t}(j) - 1)^2)PI_{C,s,t}KC_{s,t}(j) \tag{27}$$

All firms except the ones in fossil fuel extraction sectors maximise the following Lagrangian:

$$\max_{\left\{\substack{M_{s',s,t}(j),L_{skill,t}(j)\\ KD_{s,t}(j),KC_{s,t}(j)}\right\}_{t=0}^{\infty}} V_0(j) = E_0 \sum_{t=0}^{\infty} d_t\, PR_{s,t}(j)$$
$$-E_0 \sum_{t=0}^{\infty} \eta_{s,t}(j)\, d_t \left(Y_{s,t}(j) - F\left(VA_{s,t}(j), M_{s,t}(j)\right)\right), \tag{28}$$

where $\eta_{s,t}(j)$ is the Lagrange multiplier associated with the production technology and d_t is the discount factor. The following first-order conditions characterise the firms' optimising behaviour:

$$\frac{\partial V_0(j)}{\partial L_{skill,s,t}(j)} => \frac{\partial F(.)}{\partial L_{skill,s,t}(j)}\eta_{s,t}(j) - \frac{\gamma_{skill}}{2}W_{skill,t}\Delta L_{skill,s,t}(j) + \frac{\gamma_{skill}}{2}E_t\left(\frac{d_{t+1}}{d_t}W_{skill,t}\Delta L_{skill,s,t+1}(j)\right) = (1+ssc_t)W_{skill,t} \tag{29a}$$

$$\frac{\partial V_0(j)}{\partial KX_{s,t}(j)} => \frac{\partial F(.)}{\partial KX_{s,t}(j)}\eta_{s,t}(j) = i_{KX,t}PI_{X,s,t},\ X \in \{G,D,C\} \tag{29b}$$

$$\frac{\partial V_0(j)}{\partial u_{X,s,t}(j)} => \frac{\partial F(.)}{\partial u_{X,s,t}(j)}\eta_{s,t}(j) = PI_{X,s,t}KX_{s,t}(j)(\gamma_{u1} + \gamma_{u2}(u_{X,s,t}(j) - 1)) \tag{29c}$$

$$\frac{\partial V_0(j)}{\partial Y_{s,t}(j)} => \eta_{s,t}(j) = 1 - \frac{1}{\sigma_{d,s}} - \gamma_P E_t\left(\frac{d_{t+1}}{d_t}\pi_{s,t+1}(j) - \pi_{s,t}(j)\right) \tag{29d}$$

The last equation defines the price mark-up factor as function of the elasticity of substitution and price adjustment costs. We follow Burgert et al. 2019 and extend this formula with backward-looking elements in the price setting by assuming that the fraction $1\text{-}s_p$ of firms indexes prices to past inflation:

$$\eta_{s,t}(j) = 1 - \frac{1}{\sigma_{d,s}} - \varepsilon_t\ (j) - \gamma_P E_t\left(\frac{d_{t+1}}{d_t}\left(s_p\, \pi_{s,t+1}(j) + \left(1 - s_p\right)\pi_{s,t-1}(j)\right) - \pi_{s,t}(j)\right) \tag{29d'}$$

Technological progress – autonomous energy efficiency improvement and learning by doing

We incorporate two of the most often used channels in energy and climate policy models to capture technological progress[11]: *i.*) *energy efficiency improvements in using* electricity and fossil fuel and *ii.*) *productivity improvements in producing* clean capital. The first type of technological progress is modelled through autonomous energy efficiency improvement (AEEI) which implies that the energy use (i.e. electricity and fuel) per unit of output declines over time. AEEI is a frequently used approximation of energy saving technological change in Computable General Equilibrium (CGE) models. In our modelling framework, we can implement AEEI via the $ae_{F,s,t}$ and $ae_{E,s,t}$ variables, which are linked to the use of fossil fuel and electricity in equations 22 and 23. We calibrate the progress in these variables according to the documented historical trends in the literature (Weyant, 2000, Webster et al. 2008).

The second type of technological progress is modelled through learning-by-doing in our model. Learning-by-doing has been employed in the literature of energy and climate policy models to account for the simple observation that production performance either in the form of productivity or cost reductions tends to improve with the accumulation of experience. Technology "learning rates" derived from such models are now widely employed by researchers and policy analysts to project future trends in the energy and environmental domains (Rubin et al. 2015). We account for future technological progress in clean capital production in the form of learning by doing via the scaling parameter of A_s in the production function:

$$A_{C,t} = \vartheta\left(\frac{TKC_t}{TKC_0}\right)^{\zeta} \tag{30}$$

where TKC_t is the total clean capital capacity employed in the economy at time t, ϑ is a scaling factor and $\zeta = \log(1 + LR)\ /log2$ is the learning exponent, where the key parameter is the learning rate, LR, which determines the increase in productivity, or symmetrically the reduction in unit costs, as a result from a doubling of total installed clean capital in the economy.

Emission abatement

General equilibrium models in climate policy analysis may include four main types of emission abatement options: 1.) output-demand reduction, 2.) factor substitution, 3.) fuel substitution and 4.) installation of abatement equipment other than fuel substitution (see Kiuila and Rutherford, 2013). While the first option is straightforward, the last three options are more difficult to address. Integrated assessment models which link all emissions to aggregate output (e.g. Nordhaus, 2013), define an abatement cost function to address the last three options in one single function: firms can reduce their emissions by paying an abatement cost which is proportional to their output. Similar to the CGE models in the field with more elaborated sectoral structure, our model can endogenously address the first three options for energy related emissions without the need to define an abatement cost function

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[11] See Sue Wing (2006) for a comprehensive discussion of technology progress in energy and climate policy modelling.

in terms of aggregate output. To some extent, the fourth option is also included because firms can achieve fuel efficiency improvements by partially applying some kind of electrical equipment (e.g. hybrid engines) to reduce their fuel use. The CES structure also allows for (imperfect) substitution between the capital-energy composite and other, non-energy related capital (e.g. from construction sector). Investments in the latter form of capital can be interpreted as energy efficiency investments in buildings without fuel-switching.[12] However, we must also acknowledge that a large part of GHG emissions cannot be linked to the use of fossil fuel in energy production. In order to model the possibility of abating non-energy GHG emissions, which is our second source of GHG emissions, we introduce a separate abatement cost function in the emission intensive sector (T) subject to this type of emissions. The abatement cost specification follows the widely used Nordhaus (2013) functional form in the literature (e.g. Heutel, 2012). Let us define the non-energy GHG emission ($GHG_{T,t}$) of sector T as

$$GHG_{T,t} = (1 - \Theta) ghgint_T Y_{T,t}, \tag{31}$$

where $ghgint_T$ is the emission intensity of production per unit of sector T product, and Θ is the fraction of emissions abated. The cost of abating Θ fraction of emissions is given as a ratio of total output: $\psi_1 \Theta^{\psi_2} Y_{T,t}$. The parametrisation of this abatement cost function (ψ_1 and ψ_2) follows Nordhaus (2013). Parameter ψ_1 is a technological coefficient corresponding to the cost of a backstop technology, i.e.: 100% removal of non-energy GHG emissions while the exponent ψ_2 indicates a convex cost function. Given a certain carbon price, $pcarbon_{T,t}$ to pay after their emissions, firms in this sector face a modified maximisation problem in which they also have to optimise their emission abatement efforts (Θ):

$$\max_{\begin{Bmatrix} M_{s',T,t}(j), L_{skill,t}(j) \\ KD_{T,t}(j), KC_{T,t}(j) \end{Bmatrix}_{t=0}^{\infty}} V_0(j) = E_0 \sum_{t=0}^{\infty} d_t \, PR_{s,t}(j) - pcarbon_{T,t}(1 - \Theta) ghgint_T Y_{T,t} - \psi_1 \Theta^{\psi_2} Y_{T,t}$$

$$-E_0 \sum_{t=0}^{\infty} \eta_{T,t}(j) \, d_t \left(Y_{T,t}(j) - F\left(VA_{T,t}(j), M_{T,t}(j)\right)\right), \tag{28'}$$

Exhaustible resources

The profit maximisation problem of firms in the fuel sector is more involved because these firms also face a resource constraint. For simplicity, it is assumed that one unit of the exhaustible resource is transformed into one unit of fossil fuel output, therefore, in each period a $Y_{FUEL,t}(j)$ quantity of the exhaustible resource is extracted by firm j.[13] It is assumed that the exhaustible resource has a currently known size S_t for each firm and there is an exogenous detection rate g. Therefore, the profit maximisation problem involves an additional resource constraint compared to the one in eq. (28):

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[12] The advantage of addressing abatement in this way is that many of the abatement options are in fact one-time investments (e.g. insulation) and not recurring costs as in simple abatement cost functions which are defined in terms of current output. As we use CES functions at each node of production, some additional (imperfect) substitution between the capital-energy composite and other intermediate goods is also possible in the model. All of these factor and intermediate goods substitution channels are triggered by the change in relative prices, either because of an actual carbon tax or shadow price on fuel (due to regulation). As pointed out earlier, we model the aggregate abatement efforts for a group of sectors which face different abatement technologies. For a more detailed sectoral treatment of abatement options see Weitzel et al. (2019). The authors integrate enhanced bottom-up abatement curves into their large-scale numerical model. However, the level of sectoral emission detail in these types of large scale CGE models goes beyond the scope of our modelling framework.

[13] Formally, the production function for the dirty sector can be written as: $Y_{FUEL,t}(j) = min(F(.), R_F(j))$, where $R_F(j)$ is the quantity of extracted exhaustible resource and $F(.)$ captures the production process necessary for extraction and transformation of the exhaustible resource into fossil fuel.

$$\max_{\left\{\substack{M_{s',F,t}(j),L_{skill,t}(j)\\ KD_{F,t}(j),KC_{F,t}(j)}\right\}_{t=0}^{\infty}} V_0(j) = E_0 \sum_{t=0}^{\infty} d_{F,t}\, PR_{F,t}(j)$$

$$-E_0 \sum_{t=0}^{\infty} \eta_{F,t}(j)\, d_{F,t} \left(Y_{F,t}(j) - F\left(VA_{F,t}(j), M_{F,t}(j)\right)\right)$$

$$-E_0 \textstyle\sum_{t=0}^{\infty} \varphi_{s,t}(j)\, d_{F,t} \left(S_t(j) - (1+g)S_{t-1}(j) + Y_{F,t}(j)\right), \tag{32}$$

which implies a modified Hotelling-rule for the first order condition of exhaustible resource stocks:

$$\frac{\partial V_0(j)}{\partial S_t(j)} => \frac{\varphi_{s,t+1}(j)}{\varphi_{s,t}(j)} = \frac{d_{F,t}}{d_{F,t+1}(1+g)} \tag{33}$$

The Lagrange multiplier, $\varphi_{s,t}(j)$ can be interpreted as a scarcity rent and (33) is the modified Hotelling-rule with non-zero fossil fuel detection rate. Note that the first order condition w.r.t. production will also change:

$$\eta_{s,t}(j) = 1 - \frac{1}{\sigma_{d,s}} - \varphi_{s,t}(j) - \gamma_P E_t \left(\frac{d_{t+1}}{d_t}\left(sfp\, \pi_{s,t+1}(j) + (1-sfp)\pi_{s,t-1}(j)\right) - \pi_{s,t}(j)\right) \tag{34}$$

or in other words, firms in the exhaustible resource sector set their prices with a mark-up over the marginal costs plus the scarcity rent[14].

2.3. TRADE LINKAGES

All goods and services are tradable across the regions. In order to facilitate the notation, let $Z_{s,t}$ the demand by households (*C*), firms (*M*) and the government (*G*) for a particular product from sector *s*, given by the following CES functions between domestically produced ($Z_{s,t}^{D}$) and imported goods ($Z_{s,t}^{M}$):

$$Z_{s,t} = \left((1-s_{m,s,Z})^{1/\sigma_Z}(Z_{s,t}^{D})^{(\sigma_Z-1)/\sigma_Z} + s_{m,s,Z}{}^{1/\sigma_Z}(Z_{s,t}^{IM}(1-\Gamma_{s,Z,t}^{IM}))^{(\sigma_Z-1)/\sigma_Z}\right)^{\sigma_Z/(\sigma_Z-1)} \tag{35}$$

The elasticity of substitution between domestic and imported goods is σ_Z (Armington elasticity) and $s_{m,s,Z}$ is the preference parameter.

The term $\Gamma_{s,Z,t}^{IM} \equiv \frac{\gamma_{s,Z}^{IM}}{2}\left(\frac{Z_{s,t}^{IM}/Z_{s,t-1}^{IM}}{Z_{s,t}/Z_{s,t-1}} - 1\right)^2$ captures import adjustment costs that enter the resource constrant of the economy. The modelling of import adjustment costs is equivalent to the approach in Coenen et al. (2018).

The price index for each final consumption and intermediate good ($PZ_{s,t}$) is composed of the domestic and imported goods prices ($P_{s,t}^{D}$, $P_{s,t}^{IM}$) of sector *s* plus ad valorem ($TZ_{s,t}^{D}$, $TZ_{s,t}^{IM}$) and quantity taxes ($QZ_{s,t}^{D}$, $QZ_{s,t}^{IM}$) :

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[14] For the solution method, we must introduce a risk premium linked to the depletion of exhaustible resource stock. Implicitly, this risk-premium helps to factor in the higher extraction cost of depleting resources.

$$PZ_{s,t} =$$

$$\left((1 - s_{m,s,Z})(P_{s,t}^{D}(1 + TZ_{s,t}^{D}) + QZ_{s,t}^{D})^{1-\sigma_Z} + s_{m,s,Z}((P_{s,t}^{IM}(1 + TZ_{s,t}^{IM}) + QZ_{s,t}^{IM})(1 - \mathit{\Gamma}_{s,Z,t}^{IM}))^{1-\sigma_Z}\right)^{\frac{1}{1-\sigma_Z}} \tag{36}$$

Import demand by demand components is:

$$Z_{s,t}^{IM} = s_{m,s,Z}\left(\frac{1}{\mathit{\Gamma}_{s,Z,t}^{M'}}\frac{(P_{s,t}^{IM}(1+TZ_{s,t}^{IM})+QZ_{s,t}^{IM}}{PZ_{s,t}}\right)^{-\sigma}\frac{Z_{s,t}}{1-\mathit{\Gamma}_{s,Z,t}^{M}}, \tag{37}$$

where $\mathit{\Gamma}_{s,Z,t}^{M'} \equiv \partial((1 - \mathit{\Gamma}_{s,Z,t}^{M})Z_{s,t}^{M})/\partial Z_{s,t}^{M}$.

Total imports of sector *s* products ($IM_{s,t}$) are the sum of imports by users:

$$IM_{s,t} = \sum_Z Z_{s,t}^{IM}. \tag{38}$$

$IM_{s,t}$ imports are also a CES bundle of bilateral imports from foreign regions *f* ($IM_{s,t}^{f}$):

$$IM_{s,t} = \left(\sum_f \left(s_{s,t}^{IM,f}\right)^{\frac{1}{\sigma_1}}\left(IM_{s,t}^{f}(1 - \mathit{\Gamma}_{s,t}^{IM,f})\right)^{\frac{\sigma_1-1}{\sigma_1}}\right)^{\frac{\sigma_1}{\sigma_1-1}}, \tag{39}$$

where σ_1 is the elasticity of substitution between imports of different origins, $s_{s,t}^{IM,f}$ is the steady-state share of region *f* in the domestic economy's imports, and $\mathit{\Gamma}_{s,t}^{IM,f} \equiv \frac{\gamma^{IM,f}}{2}\left(\frac{IM_{s,t}^{f}/IM_{s,t-1}^{f}}{IM_{s,t}/IM_{s,t-1}} - 1\right)^2$ are bilateral import adjustment costs. The demand for goods from region *f* is given by sector and trading partner specific prices and taxes:

$$IM_{s,t}^{f} = s_{s,t}^{IM,f}\left(\frac{1}{\mathit{\Gamma}_{s,t}^{IM,f\prime}}\frac{(P_{s,t}^{IM,f}(1+T_{s,t}^{IM})+Q_{s,t}^{IM}}{P_{s,t}^{IM,f}\cdot(1+T_{s,t}^{IM,f})+Q_{s,t}^{IM,f}}\right)^{-\sigma_1}\frac{IM_{s,t}}{1-\mathit{\Gamma}_{s,t}^{IM,f}} \tag{40}$$

where $\mathit{\Gamma}_{s,t}^{M,f\prime} \equiv \partial((1 - \mathit{\Gamma}_{s,t}^{M,f})IM_{s,t}^{f})/\partial IM_{s,t}^{f}$.

Total exports of the domestic economy (X_t) is the sum of all foreign regions' sectoral imports ($IM_{s,t}^{f}$):

$$X_t = \sum_f \sum_{s\in\left\{\substack{C,D,F\\E,T,RS}\right\}} IM_{s,t}^{f} \tag{41}$$

Note that equations (39), (40) and (41) are the generalised functional forms of bilateral trade with $1 \leq N_f$ trading partners. In our subsequent simulation exercise, we calibrate our model for two regions, the European Union (*EU*) and the rest of the world (*R*).

B_t^F, the net foreign asset position of the domestic economy follows the law of motion:

$$e_t B_t^F = (1 + r_{t-1}^F)e_t B_{t-1}^F + (PX_t X_t - PIM_t IM_t)/P_t \tag{42}$$

where PX_t and PIM_t are the aggregate export and import prices, r_t^F denotes real interest paid on net foreign asset denominated in the (reserve) currency of the rest of the world region and e_t is the corresponding exchange rate.

2.4. AGGREGATION

The aggregate of any household specific variable $Z_{h,t}$ in per capita terms is given by

$$Z_t = \int_0^1 Z_{h,t} dh = (1-\varsigma) Z_{l,t} + \varsigma Z_{r,t}. \tag{43}$$

Hence, aggregate consumption and employment is given by

$$C_t = (1-\varsigma) C_{i,t} + \varsigma C_{k,t} \tag{44}$$

and

$$L_t = (1-\varsigma) L_{i,t} + \varsigma L_{k,t}. \tag{45}$$

The aggregate output of capital producing sectors ($sc \in \{C, D, G\}$) should satisfy domestic final demand for durable goods by private households ($C_{dom,sc,t}$), by the government ($Gov_{dom,sc,t}$), by firms from each sectors in the economy ($I_{dom,sc,s',t}$) and their total export, $EX_{sc,t}$:

$$Y_{sc,t} = C_{dom,sc,t} + Gov_{dom,sc,t} + \sum_{s'} I_{dom,sc,s',t} + EX_{sc,t} \tag{46}$$

$sc \in \{C, D, G\}, s' \in \{C, D, F, E, G, T, RS\}$.

Apart from the energy intensive sectors, aggregate output in other sectors ($snc \in \{F, E, RS\}$) should satisfy domestic final demand for non-durable goods by private households ($C_{dom,snc,t}$), by the government ($Gov_{dom,snc,t}$), in addition to intermediate consumption demand by firms from each sectors ($M_{dom,snc,s',t}$) and total export, $EX_{snc,t}$:

$$Y_{snc,t} = C_{dom,snc,t} + Gov_{dom,snc,,t} + \sum_{s'} M_{dom,snc,s',t} + EX_{snc,t} \tag{47}$$

$snc \in \{F, E, RS\}, s' \in \{C, D, F, E, G, T, RS\}$

Finally, the aggregate output of the energy intensive sector differs from equation 47 above because firms in this sector have to account for the cost of abatement which is expressed as μ share of total output:

$$Y_{T,t} = C_{dom,T,t} + Gov_{dom,T,t} + \sum_{s'} M_{dom,T,s',t} + EX_{T,t} + \mu Y_{T,t} \tag{48}$$

$s' \in \{C, D, F, E, G, T, RS\}$

2.5. ENVIRONMENTAL POLICIES: TAXING CARBON, SUBSIDIES AND REGULATION

At this point, a couple of remarks are necessary before turning to the governments' budget constraint in the next section. First, note that by linking quantity taxes to the carbon content of goods, quantity taxes ($QZ^D_{s,t}$, $QZ^{IM}_{s,t}$) can be used to introduce targeted carbon (border) taxes in the model. For example, denote the carbon intensity of fossil fuel used by households by co_2int_C and the price of carbon by P_{CO2}, the carbon tax paid by households according to their fuel consumption can be expressed as:

$$QC^D_{F,t} \cdot C^D_{F,t} + QC^{IM}_{F,t} \cdot C^{IM}_{F,t}, \text{ where } QC^D_{F,t} = QC^{IM}_{F,t} = P_{CO2} \cdot co_2int_C \tag{49}$$

Second, the negative values for our ad valorem and quantity tax variables are equivalent to price and quantity subsidies in policy simulations. Therefore, subsidies on the purchase of clean capital can be captured by variables $TZ^{D}_{C,t}, QZ^{D}_{C,t}$ and $TZ^{IM}_{C,t}, QZ^{IM}_{C,t}$ for domestic and imported clean goods respectively in ad valorem or quantity terms. The government can also use the revenues from carbon taxation to reduce capital or labour income taxes, increase transfers or cut lump-sum taxes. Third, the model can account for regulations, emission limits without direct fiscal revenues (e.g. obligatory emission reduction) by introducing an additional quantity constraint for sector specific fossil fuel use in the firm's profit maximisation constraint. The Lagrange-multiplier of the new constraint is the corresponding shadow price without direct fiscal implications on the government's budget.

Following the literature of integrated assessment models (e.g. Golosov et al., 2014, Nordhaus, 2014) one can also include the potential environmental feedback effects, but this extension is left for future model extensions.[15]

2.6. FISCAL AND MONETARY POLICY

Each region has its own a fiscal and monetary authority. The government finances government consumption (G_t), government investment (IG_t), transfers (TR_t), unemployment benefits (BEN_t) and subsidies (S_t). Taxes on households, foreign and domestic firms finance current fiscal expenditures and interest payments on government debt. Monetary authorities follow a standard Taylor-rule to smooth interest response to shocks hitting their economies.

2.6.1. Fiscal rules

Nominal transfers (TR_t), government purchases (G_t) and investment (IG_t) are a constant share ($\overline{tr}, \overline{g}, \overline{ig}$) of GDP:

$$TR_t = \overline{tr}GDP_t,\ G_t = \overline{g}GDP_t, \text{ and } IG_t = \overline{ig}GDP_t. \tag{50}$$

The public capital stock, which enhances productivity in sectoral value-added (eq. 17) accumulates according to:

$$KG_t = IG_t + (1-\delta_g)KG_{t-1} \tag{51}$$

The unemployed receive a share of nominal wages as unemployment benefits:

$$BEN_t = \sum_{skill\in\{L,M,H\}} bW_{skill,t}\, s_{skill}(1 - NPART_{skill,t} - L_{skill,t}), \tag{52}$$

where b is the benefit replacement rate, and s_{skill} is the population skill-share.

Government revenues R_t^G are made up of (net) ad valorem and quantity taxes on final and/or intermediate consumption, taxes on capital and labour income and lump sum taxes (TAX_t):

$$R_t^G = \underbrace{\sum_{s'}\left(\left(PC^{D}_{s',t}TC^{D}_{s',t} + QC^{D}_{s',t}\right)C^{D}_{s',t} + \left(PC^{IM}_{s',t}TC^{IM}_{s',t} + QC^{IM}_{s',t}\right)C^{IM}_{s',t}\right)}_{tax-revenue\ (net\ of\ subsidies)\ on\ final\ consumption}$$

$$\underbrace{\sum_{s'}\sum_{s}\left(\left(PM^{D}_{s',s,t}TM^{D}_{s',s,t} + QM^{D}_{s',s,t}\right)M^{D}_{s',s,t} + \left(PM^{IM}_{s',s,t}TM^{IM}_{s',s,t} + QM^{IM}_{s',s,t}\right)M^{IM}_{s',s,t}\right)}_{tax-revenue\ (net\ of\ subsidies)\ on\ intermediate\ consumption} \tag{53}$$

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[15] The literature points to large uncertainties surrounding different environmental feedback channels. Pindyck (2013) gives an in-depth critical view of them, arguing that many of the inputs are arbitrary, and the climate change modules often lack theoretical or empirical underpinnings.

$$+\underbrace{\sum_{X\in\{C,D\}}\left(t_K\left(i_{KX,t-1}-\delta_{KX}\right)P_{IX,t-1}KX_{r,t-1}\right)}_{tax\ on\ capital}+$$

$$\underbrace{\sum_{skill\in\{L,M,H\}}\left(t_{w,skill,t}+ssc\right)W_{skill,t}\,s_{skill}L_{skill,t}}_{tax\ on\ labour}+TAX_t$$

Real government debt (B_t) evolves according to

$$B_t=(1+i_{t-1}^{g}-\pi_t)B_{t-1}+G_t+IG_t+TR_t+BEN_t-R_t^G. \tag{54}$$

where we define $i_t^g=\rho_{ig}i_{t-1}^g+\left(1-\rho_{ig}\right)i_t$ in order to account for a gradual pass through of policy rates into effective government financing costs.

$$\Delta TAX_t=\tau_B\left(\frac{B_{t-1}}{GDP_{t-1}}-b^T\right)+\tau_{DEF}\Delta\left(\frac{B_t}{GDP_t}\right), \tag{55}$$

where τ_B captures the sensitivity with respect to deviations from b^T, the government debt target and τ_{DEF} controls the sensitivity of the tax-rule w.r.t. changes in the debt to output ratio.

2.6.2. Monetary policy

Monetary policy follows a Taylor rule that allows for a smoothing of the interest rate response to inflation:

$$i_t=\gamma_{ilag}i_{t-1}+\left(1-\gamma_{ilag}\right)\left(r_{EQ}+\pi_{TAR}+\gamma_{inf}\left(\pi_{C,t}-\pi_{TAR}\right)+\gamma_{ygap}\hat{y}_t\right). \tag{56}$$

The central bank has a constant inflation target (π_{TAR}) and it adjusts interest rates whenever actual consumer price inflation $\left(\pi_{C,t}\right)$ deviates from the target and it also responds to the output gap ($\hat{y}_t$) via the corresponding γ_{inf} and γ_{ygap} coefficients. [16] There is also some inertia in nominal interest rate setting over the equilibrium real interest rate r_{EQ} determined by γ_{ilag}.

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[16] With aggregated regions, this implies an assumption of similar monetary policy responses in all countries, and between euro area and non-euro area member states.

3. CALIBRATION

The calibration exploits the literature and matches selected ratios in the data, as summarised in Table 1. The remaining parameters (factor shares and productivities) have been computed from the first order conditions with respect to the choice variables. Starting from the top tier of our CES production function (see Figure 2), the elasticity between value added and intermediates (σ_{vam}) is set to 0.2 and the elasticity between intermediates is set to 0.5. These values are in the typical range used in the literature (e.g. GEM-E3, Sue Wing 2006). Within the tier of value added components, we assume a Cobb-Douglas structure between the capital composite (general and energy capital, σ_{kge}) and the labour input. The sector specific capital shares (α_s) and mark-ups (τ_s) are calibrated to match the capital/labour ratios and factor input ratios in our WIOD datasets.

One of the most important elasticities in environmental policy modelling is the substitution elasticity between GHG emitting and clean sources of energy (σ_{ke}). Acemoglu et al. (2012) argue that reasonable values should be high since fossil and non-fossil fuels should be close substitutes and they use a substitution elasticity of 3 and 10 in their low/high policy experiments between clean and dirty production. We take the value of 6 as our central elasticity. Our capital-energy composite has an elasticity of 0.5 following the GTAP-E model, which also employs a CES aggregate between capital and energy. The elasticities between domestic and imported goods and within imported goods is set to 1.5 as in our standard QUEST model set-up. Depreciation rates are set at 0.10 for the two energy intensive durables and 0.05 for non-energy durables based on OECD (2009).

Within our skill-groups, the elasticity is 1.7, which is a central estimate in Acemoglu and Autor (2011) between low and high-skilled workers. Based on Chetty (2012), the average Frisch labour supply elasticity is 0.4 in our model calibrated via the κ parameter. However, our skill-specific labour supply elasticities will be determined by the expression of $(1 - L_{skill})/(\kappa \; L_{skill})$ which yields higher elasticities for lower skilled workers with low employment rates.

Relying on detailed process-engineering models and historical trends, the AEEI parameter clusters around 1 percent per year in CGE models (Weyant, 2000), which we also apply in our baseline simulations with the corresponding annual increase in the $ae_{.,s,t}$ variable. We assume a learning rate of 10% which is closer to the lower bound of estimates in the literature (Rubin et al. 2015). Turning to our carbon cycle module, we calculate the emissions intensities from the PRIMES energy simulations in combination with the WIOD dataset. We use PRIMES data to distinguish between energy related CO_2 emissions and the rest of GHG emissions. We link the former one to the use of fossil fuels inputs from WIOD, while the latter one to non-energy GHG emissions and we use WIOD sectoral output to set the corresponding intensity. The parametrisation of the abatement cost function follows Nordhaus (2013). The exponent ψ_2 is 2.8, indicating a convex cost function, while ψ_1 is a function of time in Nordhaus (2013). We use the initial value of 0.0164 which decreases over time by 0.5%.

Table 1. **Calibration of parameter values and ratios**

Parameter	Description	Value	Sources and notes
$\sigma_{vam,s}$	eos value-added and intermediates	0.2	GEM-E3 (Capros et al. 2013)
σ_{Ms},	eos intermediates	0.5	Sue Wing (2006)
$\sigma_{kge,s}$	eos general capital and capital energy composite	1	Cobb-Douglas
$\sigma_{ke,s}$,	eos clean and dirty capital-energy composite	6	Acemoglu et al. (2012) use elasticities of 3 and 10
$\sigma_{kd,s}, \sigma_{kc,s}$	eos capital and energy	0.5	GTAP-E
α_s	sector specific capital shares	0.5-0.7	calibrated to match capital/labour ratios in IO data in WIOD (Timmer et al. 2015)
τ_s	sector specific mark-ups	0-0.4	calibrated to match factor input ratios in IO data in WIOD (Timmer et al. 2015)
σ_Z	eos domestic and imported goods	1.5	QUEST III
σ_1	eos imported goods between trading partners	1.5	QUEST III
δ_C	Depreciation rate, clean capital	0.1	OECD (2019)
δ_D	Depreciation rate, dirty capital	0.1	OECD (2019)
δ_G	Depreciation rate, other capital	0.05	OECD (2019)
μ	eos skills	1.7	Acemoglu and Autor (2011)
$\sum_{skill} s_{skill}(1-L_{skill})/(\kappa \quad L_{skill})$	Average Frisch elasticity over skill-types	0.4	Chetty (2011)
AEEI (growth rate in $ae_{.,s,t}$*)*	Autonomous Energy Efficiency Improvement	1%	Weyant (2000), Webster et al. (2008)
LR	Learning rate	0.1	Corresponds to 10% learning rate (Rubin et al. 2015)
$co_2int_{s,f'}$	CO_2 emission intensities	…	Calculated from emission data in PRIMES and WIOD
ψ_1	Abatement cost parameter	0.02	Following Nordhaus (2013)
ψ_2	Abatement cost parameter	2.8	Nordhaus (2013)

Source: WIOD, EUROSTAT and the referenced studies listed above.

4. SIMULATION SCENARIOS

4.1. REACHING THE 2050 CLIMATE NEUTRALITY TARGET

We now shift our focus to reaching the long-run climate neutrality target. Pushing our model to this limiting case offers a rich environment to illustrate the model properties through the most frequently used policy scenarios in the environmental economics literature. In particular, we test for the possibility of *double dividends*, i.e. positive environmental and economic effects of climate change mitigation policies through environmental taxes and their recycling. We implemented six scenarios to study the economic effect of reducing EU wide emissions by 94%, which corresponds to the EU’s aim of net zero emissions of greenhouse gases in 2050 after accounting for carbon sinks which are not represented in the model.

Our first reference case relies on regulations, i.e. the government imposes restrictions on the economy-wide use of fossil fuels without any additional carbon taxes. In the subsequent five scenarios, the government imposes carbon taxes such that the aggregate EU GHG emissions are reduced by 94% in 2050. We ensure the comparability of the scenarios by imposing the same emission trajectories for each sector in every scenario. We implement the scenarios by setting an exogenous (logistic) emission reduction path and by letting the model to solve for the required carbon tax (or the shadow price of carbon in the regulation scenario). We then compare the economic effects of five main different recycling options under the carbon taxation case: [17]

i.) reducing lump-sum taxes,[18]
ii.) personal income taxes (PIT) cuts for low-skilled households only,
iii.) consumption tax cuts,
iv.) reducing capital taxes (excl. dirty capital) and
v.) recycling via "clean" subsidies for supporting the purchase of clean capital goods.

We rely on the PRIMES energy model simulation results to set up a baseline which assumes the full achievement of the current 2030 climate and energy framework. All scenarios are built on a baseline that already assumes about 45% and 58% reduction of EU GHG emissions relative to the 1990 level by 2030 and 2050 respectively (see Graph 1). Both in the baseline and in the simulations we impose the corresponding PRIMES emission path for the two large emission categories: energy related CO_2 emissions from the use of fossil fuels and the non-energy GHG emissions linked to the emission intensive sector.[19] These scenarios reach an overall 52% reduction by 2030 and then reduce emissions further to 94% in 2050. Note that we focus on the direct economic effects of policies without environmental feedback.[20]

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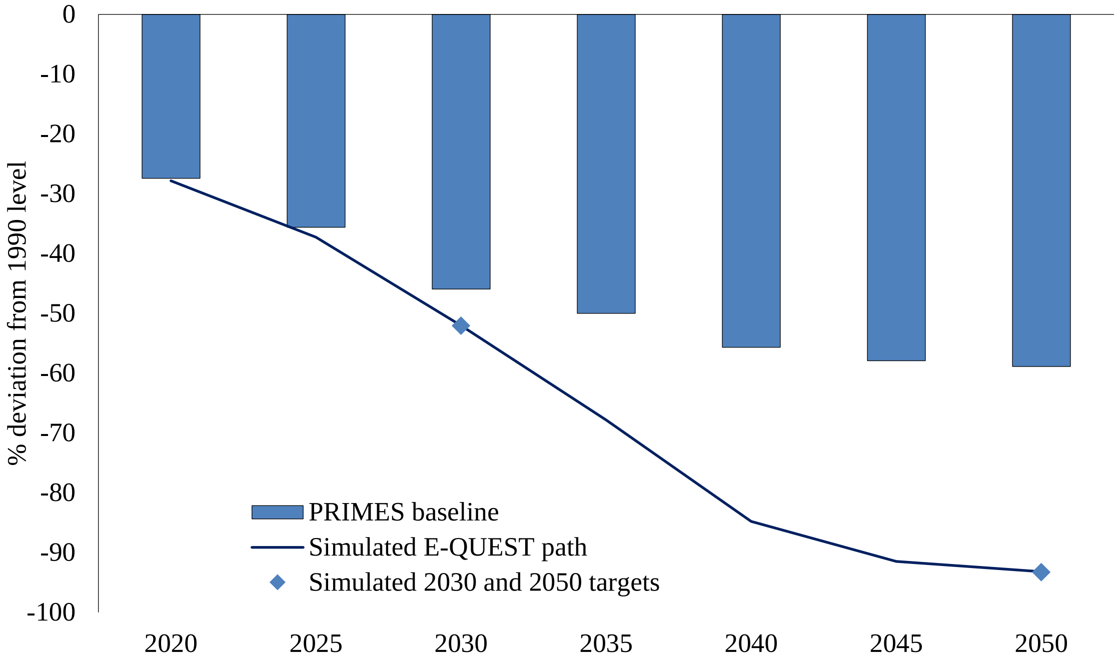
[17] There are obviously many other alternative recycling options one could consider, e.g. through public investment, or education (training, reskilling). We report here only the expenditure recycling that targets the net zero emissions objective.

[18] Lump-sum tax serves as a theoretical benchmark to compare the distortive effect of other taxes. Reducing lump-sum taxes is equivalent to giving the same lump-sum (cash) transfer to each household.

[19] Emissions are reduced at different rates for the two aggregate categories, however, within these categories we do not make additional sectoral distinction.

[20] We will examine the role of damage function(s) in a forthcoming extension of the model.

Graph 1. **Baseline and simulated GHG emission path, EU aggregate**



Source: PRIMES and E-QUEST simulations.

Graph 2 shows the evolution of GDP, consumption and employment effects up to 2050. The graphs also show the gradual transition from investing in fossil fuel intensive to electricity intensive capital as the EU approaches the emission target. Table 2 takes a snapshot of the macroeconomic effects of the different policies that achieve the EU goal of net zero emissions in 30 years (by 2050). The GDP results and the consumption effects confirm that imposing carbon taxes on the use of fossil fuel and using the revenue to reduce the burden of taxation elsewhere is economically more beneficial compared to regulatory measures, which do not yield additional tax revenues. Under regulation, GDP losses can reach about 2% in the long run, while losses are typically lower under carbon taxation, with the lowest losses when the revenue is used to reduce capital taxes or subsidise the electricity intensive durable and capital goods (-0.6%). Except for our regulation scenario, recyclable tax revenues gradually increase up to a peak and decline afterwards following a Laffer-curve shape as the more stringent emission reduction requirements command increasing carbon prices. Note that while economists tend to favour environmental taxes over non-market regulatory instruments, such as pollution standards or mandated technologies, environmental regulations are widely used for their potential benefits which cannot be captured by standard macroeconomic models[21]. In the EU climate mitigation policy, regulations and carbon prices are complementary instruments.

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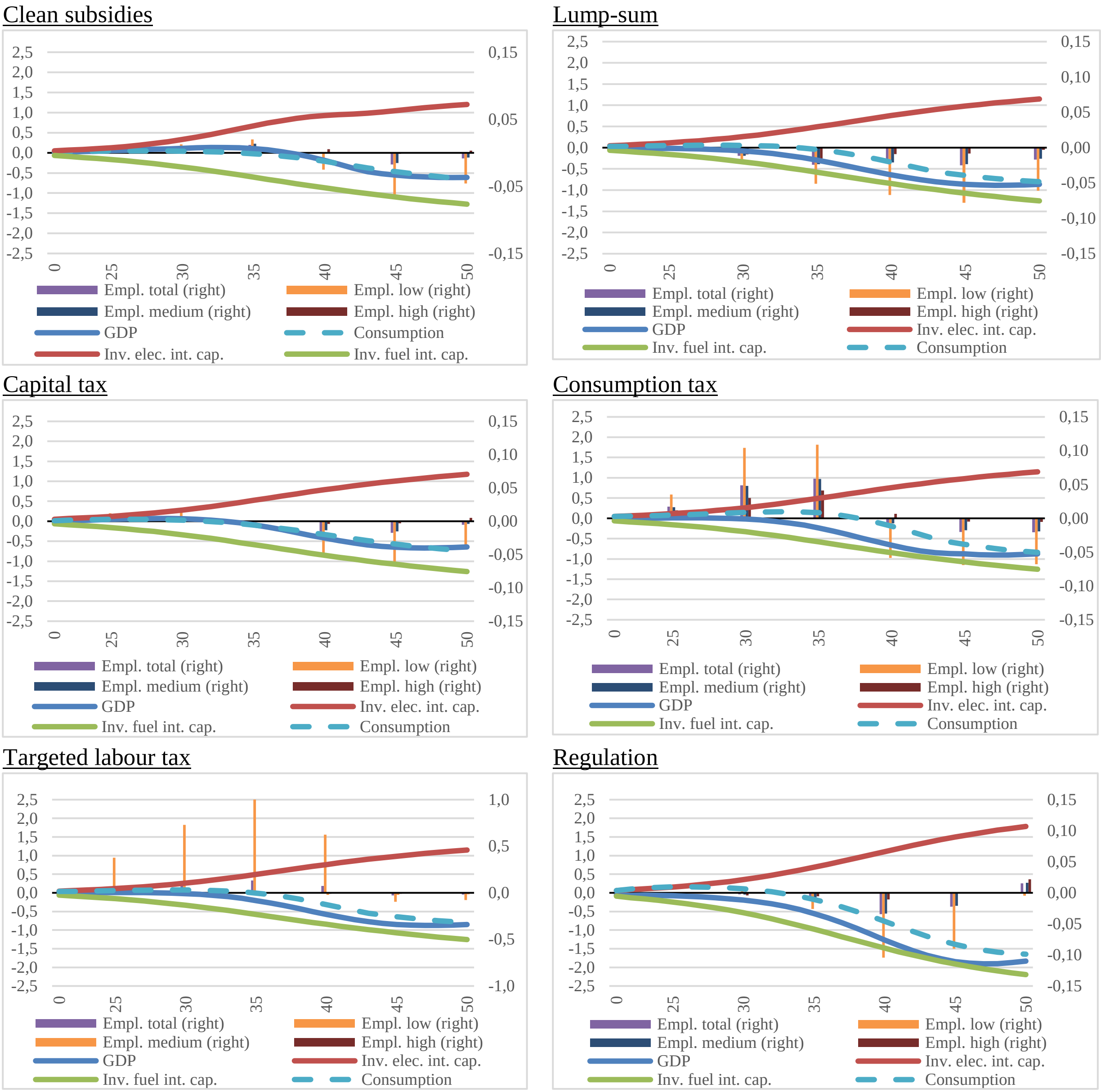
[21] According to Bovenberg and Goulder (2002) this can be partly due to the easier public acceptance of non-market instruments over taxes. It may also reflect the tendency of the political process to avoid the distributional impacts that would stem from emissions taxes. It could also reflect some efficiency disadvantages of emissions taxes that can arise in more complex settings than those considered so far: e.g. uncertainty can add further dimensions to the instrument choice, and may favour non-tax approaches. Fischer and Pizer (2019) show that while the progressive redistribution of emissions revenues can address inequality concerns between income groups, Piguvian policies may actually increase inequality within income groups, e.g. due geographic factors. Recent analysis by Temursho et al. (2020) also confirms that a regulation-based scenario to reach the 2030 EU targets may perform relatively well compared to the pricing-based scenarios in terms of horizontal equity considerations.

Graph 2. **EU GDP and employment effects of the 2050 targets under different revenue-recycling options**



Note: Different carbon tax revenue recycling options, and regulation. GDP and employment are expressed in percent deviations from baseline. Consumption, investment in electricity intensive and fuel intensive capital are shown in percent of baseline GDP. Source: E-QUEST simulations.

Table 2. **Long run contributions to GDP, expenditures approach (2050)**

	Regulation	Carbon tax with revenue recycling:				
		Lump-sum	VAT	Low sk. PIT	Capital tax	Clean subs.
GDP	**-1.83**	**-0.86**	**-0.85**	**-0.85**	**-0.64**	**-0.61**
Consumption	**-1.08**	**-0.50**	**-0.50**	**-0.50**	**-0.46**	**-0.40**
- Electricity	0.82	0.86	0.86	0.86	0.87	0.87
- Fuel	-0.68	-0.67	-0.67	-0.67	-0.67	-0.68
- General capital	-0.04	-0.01	-0.01	-0.01	-0.01	-0.01
- Dirty capital	-0.97	-1.05	-1.05	-1.05	-1.05	-1.05
- Clean capital	0.72	0.81	0.81	0.81	0.82	0.83
- Energy int.	-0.11	-0.06	-0.07	-0.06	-0.06	-0.05
- Others	-0.82	-0.38	-0.40	-0.38	-0.35	-0.31
Investment	**-0.20**	**0.06**	**0.06**	**0.06**	**0.16**	**0.12**
- General capital	0.22	0.17	0.16	0.17	0.25	0.19
- Dirty capital	-2.19	-1.25	-1.25	-1.25	-1.26	-1.28
- Clean capital	1.78	1.15	1.15	1.15	1.18	1.20
Exports	**-0.72**	**-0.79**	**-0.77**	**-0.78**	**-0.75**	**-0.73**
- Electricity	0.00	0.00	0.00	0.00	0.00	0.00
- Fuel	-0.12	-0.15	-0.15	-0.15	-0.14	-0.14
- General capital	-0.04	-0.04	-0.04	-0.04	-0.04	-0.04
- Dirty capital	-0.19	-0.19	-0.19	-0.19	-0.18	-0.18
- Clean capital	0.26	0.16	0.16	0.16	0.17	0.18
- Energy int.	-0.30	-0.33	-0.33	-0.33	-0.32	-0.32
- Others	-0.33	-0.24	-0.23	-0.24	-0.23	-0.23
Imports	**-0.62**	**-0.53**	**-0.53**	**-0.53**	**-0.52**	**-0.51**
- Electricity	0.02	0.02	0.02	0.02	0.02	0.02
- Fuel	-1.13	-1.15	-1.15	-1.15	-1.15	-1.15
- General capital	0.01	0.02	0.02	0.02	0.02	0.02
- Dirty capital	-0.61	-0.42	-0.42	-0.42	-0.42	-0.42
- Clean capital	0.85	0.72	0.72	0.72	0.73	0.73
- Energy int.	0.09	0.15	0.15	0.15	0.15	0.15
- Others	0.15	0.13	0.12	0.13	0.13	0.14

Note: Deviations measured in percent of baseline GDP. Source: E-QUEST simulations.

The ranking of GDP results by recycling instruments also reflects the ranking of taxes by their distortive effects in the economy. Reducing lump-sum taxes, which are the least distortive, have the least dampening effect on the cost of climate policy. This is followed by consumption taxes (VAT) and targeted labour tax reductions towards lower income groups with a higher marginal propensity to consume. Taxes on capital are the most distortive taxes in our experiment with the largest impact from the tax recycling scenarios. The most beneficial scenarios in terms of GDP effects are the recycling of carbon revenues into subsidies on the purchase of clean capital and the capital tax reduction. In terms of consumption losses, we can also see that subsidies given to households to help them purchasing clean durables provides the biggest cushion against the increasing burden of fuel taxation, which makes the dirty use of energy gradually more costly. Notice also that the economic costs are slowly mitigated over time as clean capital producers benefit from the learning-by-doing effect which translates into productivity improvements and lower producer price.

Table 2 above, and Tables 3 and 4 below help us to understand what drives the difference between the recycling options by decomposing the GDP effects from the expenditures and production side respectively. Starting with Table 2, we can see that the *Capital tax reduction* and *Clean subsidy* scenarios, which are the most beneficial ones from an economic point of view, perform better with the least negative effect on consumption, particularly on the consumption of non-energy related sectoral goods (Others). These two scenarios also lead to higher investment of general capital and clean capital compared to other recycling options.

Table 3: Long run change in sectoral value added (2050)

	Regulation	Carbon tax with revenue recycling:				
		Lump-sum	VAT	Low sk. PIT	Capital tax	Clean subs.
Value added contribution by sectors:						
- Electricity generation	61.2	58.9	58.8	58.9	59.3	60.0
- Fuel	-69.9	-68.8	-68.8	-68.8	-68.7	-68.8
- Gen. capital	0.1	0.2	0.1	0.2	0.6	0.4
- Dirty capital	-26.3	-19.7	-19.7	-19.7	-19.6	-19.7
- Clean capital	27.1	20.5	20.5	20.6	21.1	21.8
- Energy int.	-4.0	-3.7	-3.7	-3.6	-3.4	-3.4
- Others	-2.3	-1.0	-1.1	-1.0	-0.9	-0.8

Note: Percent deviations from baseline levels. Source: E-QUEST simulations.

Table 3 shows the level effect on sectoral value added for each scenario. We can see that from the supply side, the lower GDP losses in the Capital tax reduction and the Clean subsidy scenarios stem from stronger positive growth in the electricity and the clean capital production sectors.

Finally, Table 4 explores the contributing factors behind the sectoral value added growth. The sectoral shift from dirty to clean technologies has limited employment effects at the aggregate level across the scenarios by 2050. On the other hand, the dynamic profile of employment in Graph 2 shows that PIT reduction on low-skilled wages can account for the highest employment increase in the middle of the transition, but this employment gain evaporates as the recyclable carbon tax revenues pass their peak over time. In terms of capital accumulation, the Capital tax reduction and the Clean subsidy scenarios allow for the largest increase in general and clean capital stock while the reliance on dirty capital stays around the same level in both of these recycling scenarios.

Table 4. **Employment and capital accumulation (2050)**

	Regulation	Carbon tax with revenue recycling:				
		Lump-sum	VAT	Low sk. PIT	Capital tax	Clean subs.
Employment	-0.01	-0.02	-0.02	-0.02	-0.01	-0.01
- Electricity	65.1	65.8	65.7	65.7	65.6	66.3
- Fuel	-50.5	-50.7	-50.7	-50.7	-50.8	-50.9
- Gen. capital	0.7	0.8	0.8	0.8	1.1	0.8
- Dirty capital	-20.9	-16.5	-16.5	-16.5	-16.6	-16.7
- Clean capital	27.2	22.7	22.7	22.7	23.1	23.5
- Energy int.	-2.1	-1.8	-1.8	-1.8	-1.9	-1.9
- Others	-0.2	-0.4	-0.4	-0.4	-0.4	-0.4
Capital - general cap. stock by sectors						
- Electricity	49.5	48.4	48.4	48.5	49.7	49.5
- Fuel	-41.9	-39.6	-39.6	-39.6	-39.6	-39.6
- Gen. capital	0.0	0.1	0.0	0.2	1.0	0.4
- Dirty capital	-18.3	-13.6	-13.7	-13.6	-13.3	-13.6
- Clean capital	22.2	16.8	16.7	16.9	17.9	18.5
- Energy int.	-2.4	-1.9	-2.0	-1.9	-1.4	-1.7
- Others	-0.8	-0.8	-0.9	-0.8	-0.3	-0.6
Capital - dirty cap. stock by sectors						
- Electricity	-88.1	-97.0	-97.0	-97.0	-96.9	-96.8
- Fuel	-88.8	-99.5	-99.5	-99.5	-99.5	-99.4
- Gen. capital	-86.6	-92.2	-92.2	-92.2	-92.2	-92.1
- Dirty capital	-81.5	-63.6	-63.6	-63.6	-63.6	-63.7
- Clean capital	-80.9	-52.9	-52.9	-52.9	-52.9	-52.7
- Energy int.	-87.2	-95.1	-95.1	-95.1	-95.1	-95.0
- Others	-69.3	-29.9	-29.9	-29.9	-30.0	-30.6
Capital - clean cap. stock by sectors						
- Electricity	89.9	89.7	89.7	89.7	90.0	91.0
- Fuel	-14.9	9.9	9.9	9.9	10.1	10.0
- Gen. capital	83.6	90.3	90.2	90.3	91.7	91.8
- Dirty capital	26.8	18.9	18.9	18.9	19.3	20.0
- Clean capital	121.6	76.8	76.8	76.9	78.5	81.1
- Energy int.	81.7	92.9	92.9	93.0	93.8	94.3
- Others	76.8	34.3	34.2	34.3	35.2	37.8

Note: Percent deviations baseline levels. Source: E-QUEST simulations.

At this point, it is worth taking a snapshot of our climate policy measures in the long run by looking at how they perform along the lines of the two possible dividends: their environmental and welfare effects. Goulder (1995) surveyed the theoretical and empirical evidence on the double-dividend hypothesis and distinguished between the strong and the weak form of the double dividend. The weak form of the double-dividend hypothesis requires that the efficiency costs of a revenue-neutral environmental tax reform are lower if the additional revenues from the environmental taxes are recycled in the form of reduced distortionary taxes compared to the case that these revenues are recycled in a lump-sum fashion. The strong form of the double dividend asserts that an environmental tax reform increases not only environmental quality but also non-environmental welfare. We can focus on the GDP, consumption and employment effects of the four main carbon-revenue recycling scenarios, reducing lump-sum taxes, low-skilled labour taxes, capital taxes, VAT, or providing green (clean) subsidies. Note that by the construction of our scenarios, each of these policies yield the same environmental effects as we impose the same emission reduction path for easier comparison. However, our policies perform differently from economic benefits and welfare point of view. Our first observation is that the weak form of double dividend as defined by Goulder (1995) is easily satisfied. Recycling the revenues by reducing any of the distortionary taxes can improve the GDP, consumption or employment effect relative to our lump-sum scenario. In line with the meta-analysis of Freire-González (2017), the strong form of double dividend is much harder to achieve. In terms of GDP or welfare, our policies cannot reach positive GDP or consumption effects.

4.2. SENSITIVITY ANALYSIS

We conclude our analysis by performing a sensitivity analysis with respect to some of the most critical parameters of the model:

i.) Elasticity of substitution between the clean and dirty capital-energy bundle
ii.) Learning by doing rate
iii.) Autonomous Energy Efficiency Improvement rate
iv.) Labour supply (Frisch) elasticity

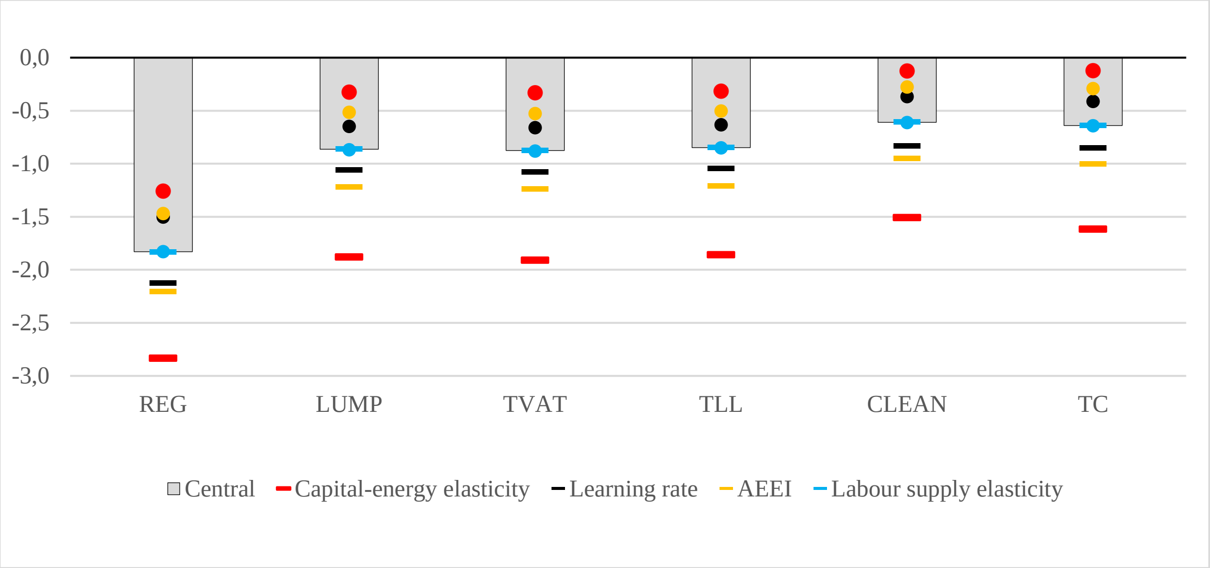
We take an interval of +/-25% of the original calibrated values for the corresponding parameters described in Table 1, approaching the lower and upper end of the estimates applied in the relevant literature.

Focusing on the GDP and employment effects, both for 2050, Graphs 3 and 4 show the sensitivity of the results using column bars for the central scenarios discussed in the previous sections and coloured markers for the lower and upper bounds for the corresponding parameters. Note that in each case, the larger (smaller) is the parameter value, the more optimistic (pessimistic) is our calibration scenario in terms the main macroeconomic variables. The graphs below offer a number of interesting insights into the sensitivity of our results and they also point to the need of future research w.r.t. to the most important parameters determining the policy outcomes.

First, the results show that while the elasticity of substitution between clean and dirty technologies plays a crucial role in the magnitude of the GDP results, they are less important for the aggregate employment effects in general. For each scenario, increasing (decreasing) the substitution possibilities between clean and dirty capacities significantly improves (worsens) the long-run GDP effects. Under the high elasticity case, the clean subsidy and the capital tax recycling scenarios can result in negligible, only slightly negative GDP effects. On the other hand, the output effects can go beyond -2.5 % under the low substitution elasticity case with solely regulation based climate policy. Similarly, we can also see that both the learning-by-doing rates and the AEEI rates have a significant effect on the GDP results. This shows that the uncertainty surrounding these factors can play an important role. On the other hand, our GDP results are robust w.r.t. the Frisch labour supply elasticity.

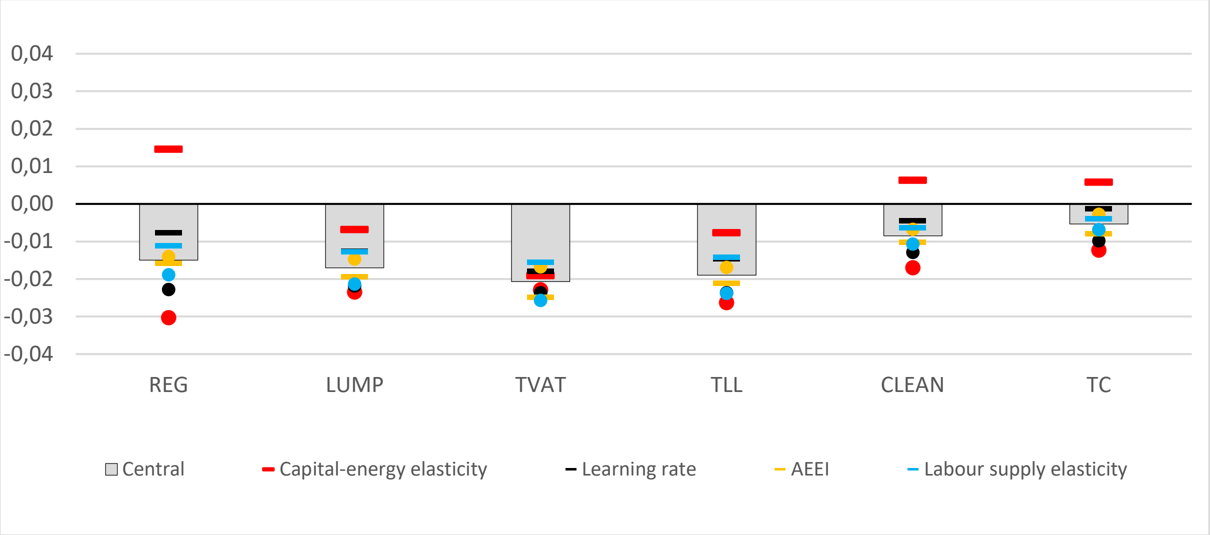
Concerning the employment effect, the clean-dirty substitution elasticity plays an important role while the learning-by-doing rates and the AEEI rates have less influence on the employment results. As would be expected, the Frisch elasticity has a strong impact on the employment outcome, in particular for the VAT and targeted labour tax reduction and the regulation scenario.

Graph 3. **EU GDP effects 2050, sensitivity analysis**



Note: Regulation as well as carbon tax revenue recycling options. Percent deviations from baseline. Source: E-QUEST simulations. Within each colour code, the round markers correspond to the upper limit and the horizontal bars mark the lower bound of the respective parameter.

Graph 4. **EU employment effects 2050, sensitivity analysis**



Note: Regulation as well as carbon tax revenue recycling options. Percent deviations from baseline. Source: E-QUEST simulations. Within each colour code, the round markers correspond to the upper limit and the horizontal bars mark the lower bound of the respective parameter.

Note that for the GDP effects the sensitivity is positively correlated to the parameter range, with lower GDP losses for the upper bounds of the respective parameters, and more negative effects for the lower bounds. The direction of sensitivity turns around for the employment effect in case of the dirty-clean elasticity and learning rates: the higher the elasticity of substitution between dirty and clean capacity or the higher the learning rate, the lower the employment effect due to the labour saving effect of technological improvements.

5. CONCLUDING REMARKS

In this paper, we have described a micro-founded multi-region DSGE model with energy sectors and used it to analyse the macroeconomic impact of climate policy related reforms in the European Union. Our focus here has been on budgetary-neutral policies to reach the net zero emission target through regulation or carbon taxes. We have not assessed the effects on growth of the green investments envisaged in the framework of the European Green Deal or the Recovery and Resilience Facility. Our main finding is that the transitional costs of moving towards a net zero emissions economy can be reduced in the long run if the revenue of carbon taxes can be used to reduce other distortive taxes or for subsidising clean energy. While we find no evidence of a strong form of double dividend, the estimated output losses of around 0.6% by 2050 are hardly significant given the scale of the energy transition. And one has to bear in mind that all this is relative to a baseline without accounting for the economic cost of climate change. If no action is taken, the economic costs of climate change will increase over time, and especially in the second half of this century become substantial (e.g. IPCC, 2018, Nordhaus 2014, Stern 2007). Mitigation polices at a global level could avoid these damages and yield net output gains compared to a scenario in which these climate costs materialise.

Our model includes some features that facilitate the transition from a carbon intensive economy to one with net zero emissions. The substitutability between dirty and clean inputs in energy generation plays a key role, while assumptions on learning by doing in the clean sector, and energy-saving technological progress are also crucial to reduce the transitional costs of decarbonisation. While our assumptions on these factors are based on historical data and trends, the sensitivity of our finding of negligible transitional costs to these assumptions underline the importance of these technological assumptions. Policies should therefore be directed to support this technological transition towards a climate neutral economy, by boosting green public infrastructure and R&D subsidies to spur innovation (as promoted in the European Union's Green Deal). In the European Union's Recovery and Resilience Facility, which provides support to the Member States of €672.5 billion in loans and grants, measures that contribute to the green transition must account for at least 37% of the recovery and resilience plan's total allocation.

In terms of future extensions of our work, following the literature of integrated assessment models (e.g. Golosov et al., 2014, Nordhaus, 2014) we can also include the potential environmental feedback effect of climate change policies by defining the carbon-cycle of atmospheric carbon concentration and by linking it to a damage function in our model. Additionally, the model also allows us to provide a more detailed view on the functional income distribution effect of climate change related policies by using a sectoral differentiation of labour demand across skill-levels.

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ANNEX: SECTORAL MAPPING

(E) Electricity provider	D35	Electricity, gas, steam and air conditioning supply
(F) Fossil fuel provider	B	Mining and quarrying
	C19	Manufacture of coke and refined petroleum products
(D) Manufacturing of capital with fossil fuel need	C28	Manufacture of machinery and equipment n.e.c.
	C29	Manufacture of motor vehicles, trailers and semi-trailers
	C30	Manufacture of other transport equipment
(C) Manufacturing of capital with electricity need	C26	Manufacture of computer, electronic and optical products
	C27	Manufacture of electrical equipment
(G) Manufacturing of general capital without direct energy need	C25	Manufacture of fabricated metal products, except machinery and equipment
	F	Construction
	C31_C32	Manufacture of furniture; other manufacturing
(T) Emission intensive sectors	A01	Crop and animal production, hunting and related service activities
	A02	Forestry and logging
	A03	Fishing and aquaculture
	C13-C15	Manufacture of textiles, wearing apparel and leather products
	C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
	C17	Manufacture of paper and paper products
	C20	Manufacture of chemicals and chemical products
	C23	Manufacture of other non-metallic mineral products
	C24	Manufacture of basic metals
	H49	Land transport and transport via pipelines
	H50	Water transport
	H51	Air transport
	H52	Warehousing and support activities for transportation
	H53	Postal and courier activities
(RS) Rest of sectors	C10-C12	Manufacture of food products, beverages and tobacco products
	C18	Printing and reproduction of recorded media
	C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
	C33	Repair and installation of machinery and equipment
	E36	Water collection, treatment and supply
	E37-E39	Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services

G45	Wholesale and retail trade and repair of motor vehicles and motorcycles
G46	Wholesale trade, except of motor vehicles and motorcycles
G47	Retail trade, except of motor vehicles and motorcycles
I	Accommodation and food service activities
J58	Publishing activities
J59_J60	Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities
J61	Telecommunications
J62_J63	Computer programming, consultancy and related activities; information service activities
K64	Financial service activities, except insurance and pension funding
K65	Insurance, reinsurance and pension funding, except compulsory social security
K66	Activities auxiliary to financial services and insurance activities
L68	Real estate activities
M69_M70	Legal and accounting activities; activities of head offices; management consultancy activities
M71	Architectural and engineering activities; technical testing and analysis
M72	Scientific research and development
M73	Advertising and market research
M74_M75	Other professional, scientific and technical activities; veterinary activities
N	Administrative and support service activities
O84	Public administration and defence; compulsory social security
P85	Education
Q	Human health and social work activities
R_S	Other service activities
T	Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
U	Activities of extraterritorial organisations and bodies

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