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Contribution to the Project

The research paper points towards the impact of policy instruments in the eco-innovation domain on economic growth and environmental performance. The research carried out in this paper develops novel methodology to assess the role of innovation in a macroeconomic context. The model comprise different sectors and focuses on the EU area. The results will contribute to the questions of smart, sustainable and inclusive growth.

Keywords:

Ecological innovation, Economic growth path, Industrial policy, Innovation, Innovation policy, Intangible assets, New technologies, Sustainable growth

Jel codes:

O31, O40, O41

Investment-specific vs Process Innovation in a CGE model of Environmental Policy

Claudio Baccianti and Andreas Löschel*

Abstract

The European Union has implemented demand push and technology pull policies to foster innovation on the energy and resource efficiency of capital goods. The state of the art of general equilibrium modelling applied to environmental policy rarely treats product and process innovation separately and product quality is, in the best case, exogenous. We develop a dynamic multi-sector CGE model that distinguishes between R&D-based process innovation for all firms, endogenous product innovation in the capital good sector and adoption decisions with respect to the installation of new capital vintages in the rest of the economy. Our results support the previous literature in finding that aggregate innovation declines following an energy tax but whereas process innovation is reduced, product innovation actually rises. We find that demand pull policies are less effective than product-related R&D subsidies to reduce aggregate energy intensity.

1 Introduction

Innovation is one of the pillars of the Europe 2020 strategy to foster smart, sustainable and inclusive growth up to 2020 and beyond. Public support to technological progress is seen as a key policy measure to address environmental issues and to strengthen the European economy at the same time. Green technologies set a bridge between innovation and environmental policy and they are expected not only to reduce pollution and resource use but as well to positively contribute to economic growth and employment creation. In this paper we focus on energy efficiency technologies and try to understand whether these policies, as R&D subsidies

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and energy taxes, are characterized by synergies in terms of economic and environmental goals or they rather carry trade-offs that are understated in the policy debate. The Europe 2020 Strategy sets a specific target to increase overall energy efficiency by 20% in 2020. A broad range of policies has been introduced to trigger the improvement in energy efficiency of industrial processes, buildings and transport systems. The 2011 Energy Efficiency Plan includes a comprehensive set of measures, ranging from *demand pull* policies on technology adoption to *technology push* research programs. On the demand side, the 2012 Energy Efficiency Directive introduces energy labeling, energy efficiency standards and promotes the direct support for investing in energy conservation in the public and private sector. On the supply side of technologies, the Strategic Energy Technology Plan is designed to foster innovation on a wide spectrum of low-carbon technologies and it gives an important role to R&D subsidies directed to research on energy efficiency. The following Horizon 2020 research program allocates about 100 millions of euros for the period 2014-2020 to research projects on energy conservation technologies under the Energy Efficiency Call 2015.

Despite the important role of such measures in economic policy, the understanding of their macroeconomic impact has been so far incomplete. One well established approach for the ex-ante analysis of innovation and environmental policies is the use of Computable General Equilibrium (CGE) models, which are able to give estimates of macroeconomic effects by taking into account the complex interactions between agents in the economy. Several CGE studies have analysed European environmental policies in details (e.g. Hübler and Löschel, 2013; Commission, 2014) but only very few have engaged in the challenging task to take innovation into the analysis. Without endogenous innovation the modelling exercise can only give a limited view on how environmental policy interacts with technological progress and policy instruments targeting technology cannot be fully assessed. Subsidies on the purchase of more energy efficient capital goods are not only expected to promote the replacement of inefficient technologies, but as well to trigger an acceleration in the development of products with higher productivity. A model with exogenous product quality can say very little about this important effect.

We develop a multisector dynamic model in which the quality of durable goods is endogenous and driven by product innovation in the capital good sector. Moreover, the model features two distinct sources of productivity gains: not only improvements in the quality of capital goods but as well in-house process innovation, modelled using the knowledge stock specification (e.g. Goulder and Schneider, 1999; Otto et al., 2008; Bosetti et al., 2009; Kristkova, 2012). The distinction is relevant in a multisector economy because some sectors might have low R&D spending but still high productivity growth. An example is agriculture, which has a very low R&D intensity but it is highly capital intensive and the investment in new machines and equipment is the main channel of productivity growth[1]. Empirical studies have confirmed that the productivity impact of in-house R&D might be overestimated if interindustry technology flows are neglected (Scherer, 1982; Griliches and Lichtenberg, 1984).

Another noteworthy feature of our model is that capital quality is energy-saving. In standard models of product innovation, quality is purely capital-augmenting and this specification delivers equivalent results compared to a model with cost-cutting process innovation[2]. Under that assumption, from the point of view of firms demanding investment goods there would be no difference between a lower price of capital and higher quality, both decreasing production costs to the same extent. Instead we assume capital quality to be energy-saving. In a complete production function with several inputs, a reduction in the price of investment goods might trigger higher use of capital and raise the demand for other inputs, including energy. In our model the increase in quality of the latest capital vintage does not give the same outcome, having instead a net energy-saving effect. As a result, we are able to analyse an innovation policy that fosters general (unbiased) productivity through process innovation, separately from funding targeting R&D on energy conservation technologies.

We calibrate the model to input-output data for the European economy and perform policy simulation exercises that focus on some innovation and environmental policy instruments. The purpose of this paper is not to provide a precise quantitative assessment of existing European policies, but rather to exploit the novel modelling set-up to study the interaction between these two policy dimensions. Is an energy tax able to address environmental issues and to trigger faster technological progress? Which innovation policy is most effective in reducing energy intensity? We find that the increase of energy costs through taxation is effective in curbing energy demand but it is detrimental for final consumption and for the overall pace of technological progress. Process innovation in all consumption good sectors declines following the introduction of an energy tax, showing that the market size is an important determinant of innovation incentives in our model. This result is not surprising and is in line with previous findings (e.g. Goulder and Schneider, 1999; Sue Wing, 2003). Yet, we find that firms in the capital good sector seize the opportunity of higher energy costs and increase both R&D spending and production. Researchers in that sector exploit the higher willingness to pay of other firms for investment goods with higher embodied quality. As a result, investment good producers redirect innovation towards product innovation and the quality of durable goods increases substantially in this scenario.

[1] In all sectors firms have a much higher capital-intensity than knowledge-intensity, which suggests that investment-specific technological progress might be more important than pure process innovation.

[2] See for instance Acemoglu (2009), Ch. 12.

With respect to environmental goals, financing R&D spending results to be more effective than a demand pull policy on capital investment to reduce energy intensity and energy demand. The subsidy on the purchase of new capital goods is able to boost investment spending but has a modest effect on product innovation and deters process-related R&D investment in consumption good sectors. In all policy scenarios the capital vintage structure is a crucial channel of policy intervention. Short term negative effects on the quality of investment goods reverberates in the long run: accumulating physical capital with lower embodied productivity has detrimental effects for economic growth and energy efficiency over time. Our findings suggest that policy design should carefully consider the implications for investment-specific technological change.

This report is structured as follows. In Section 2 we explore into more details the existing literature on CGE models with endogenous technological change and discuss how different types of innovation have been modeled so far. Section 3 includes the model description, using a simplified version to better explain the analytical features of the model. Section 4 illustrates the process of data collection and calibration of the full CGE model version. Section 5 contains an overview of the main policy simulation exercises. Section 6 concludes.

2 Innovation in Applied General Equilibrium Models

The field of applied general equilibrium modelling with endogenous technological change is extensive, even within the narrow study of environmental policies. Therefore we refer to existing reviews of the literature for a complete overview, e.g. Gillingham et al. (2008); Carraro et al. (2010); Löschel and Schymura (2013), and we focus on the issues more closely related to our work. Bottom-up models have a very detailed representation of energy technologies and learning curves well capture the effects of time and production scale on productivity changes for technologies actively used in production. Macroeconomic models and multisector CGE models have instead adopted alternative technology specifications, that put more emphasis on innovation and investment in R&D activities. These studies borrow from the theoretical literature about endogenous growth (e.g. Romer (1990); Aghion and Howitt (1992)) and make the necessary compromises with the complexities typical of applied large-scale models. The knowledge stock specification is one popular example. Firms can substitute out physical inputs for intangible assets like patents, know-how and structural capital (the non-physical infrastructure of a company), but as well human capital might be included. Knowledge is accumulated through R&D investment, which is produced by research and innovation activities. The modelling of knowledge accumulation is similar to the traditional capital accumulation process and it reflects the view that R&D expenditures are dedicated to build up production assets, intangibles, and are not simple intermediate expenditures. The representation of knowledge with stock variables is also well suited to account for the intertemporal and intratemporal spillovers that are typical of research and innovation activities.

Learning-by-doing, knowledge stocks, as well as other modelling approaches as backstop technologies, provide a stylized but effective framework to endogenize technological progress. However technological change is a complex phenomenon and can be hardly represented in full details. For instance, as learning-by-doing emphasises the role of experience and technological progress on a specific technology, it has little to say on how research and innovation are directed towards specific factors of production or specific sectors. The knowledge stock specification is better able to capture how R&D investment reacts to changes in commodity and input prices, as well as market size effects that affect research incentives. Yet innovation is performed in different varieties, from product to organizational innovation, from radical to incremental and from exploration to exploitation innovation. Such heterogeneity is somehow neglected in the state of the art of applied modelling, but it might be important. Baccianti and Löschel (2014) ask to which extent product and process innovations are depicted in CGE modelling work about environmental policy. By reviewing the existing literature, they argue that in most cases only process innovation is taken into account and in some cases, like backstop technologies, the modelling of innovation can be interpreted either way. The equivalence of product and process innovation when quantities and quality are perfect substitutes is indeed a classic result in macroeconomics, in particular in endogenous growth theory. SEURECO/ERASME (2014) is one of the very few applied large-scale modelling studies to date that models product and process innovation separately, including two distinct types of knowledge stocks, one with a direct effect on the demand curve and another with a direct effect on production costs.

Our work is as well related to the literature about Investment-Specific Technological Change (ISTC) (e.g. Greenwood et al., 1997; Cummins and Violante, 2002; Ngai and Samaniego, 2009), which focuses on the contribution of innovation in the capital goods sector to explain macroeconomic phenomenona like economic growth and business cycle fluctuations. ISTC is a type of non-neutral technological change that makes the production of capital goods more efficient and in each period one unit of new equipments contributes more to the production of output. That is, the price of capital goods - in terms of output - declines over time as data shows. The structure of our model is similar to Dürnecker and Mand (2013), a study that analyses the impact of product market reforms on the US economy. In their model the quality of investment goods is endogenous and capital good producers are heterogeneous. The multisector economy has an input-output structure, which boosts the effect of ISTC on aggregate productivity, as also shown in Ngai and Samaniego (2009). Our model differs not only for the research question, but also for the different interpretation of capital productivity - that we extend to energy efficiency - and the joint modelling of both product and process innovation.

3 A Multi-Sector Model with Capital-embodied Technological Change and Process Innovation

The core structure of the model is a dynamic multi-sector model of an open economy, that is extended to include process-related knowledge capital formation and a separate module dedicated to the production and innovation decisions in the investment good sector. This section presents a stylized version to have a clearer view on the model behaviour, ignoring for the moment the use of national and international intermediates. The next section presents the full-fledged version used for policy simulations.

The fully intertemporal model allows agents to have forward looking decisions on a finite horizon. The intertemporal maximization framework is important for the modelling of innovation: the incentive to engage in R&D is in fact dependent on the future economic conditions in which the technology will be marketed. Because of imperfections related to the marketing of new ideas, we follow the literature and assume that the innovator is able to appropriate the stream of future rents generated by the production of the new technology. The resulting market microstructure is characterised by imperfect competition as in classic models of endogenous growth (e.g. Judd, 1985; Romer, 1990; Aghion and Howitt, 1992) and in previous CGE studies dealing with innovation (e.g. Diao et al., 1996; Otto et al., 2007, 2008; Roeger et al., 2008). We assume knowledge to be sector-specific. Within each sector the successful innovator obtains monopoly rights on the use of the patented idea, which allows the firm to have positive profits. In consumption good sectors firms compete on prices through process innovation, whereas in the capital good sector R&D activities can target both process and product innovation. The energy sector supplies energy to the rest of the economy and does not perform R&D activities.

3.1 Households and Final Demand

The representative household maximises the present value of lifetime utility U under a finite horizon T:

$$U = \sum_{t=0}^{T} \left(\frac{1}{1+\rho} \right)^{t} u(C_t), \tag{1}$$

where C_t is a bundle of final consumption goods and ρ is the discount factor. We follow the literature and assume that the instantaneous utility function $u(C_t)$ is characterized by constant elasticity of intertemporal substitution,

$$u(C_t) = \frac{C_t^{1-\theta} - 1}{1-\theta},$$

given θ, the inverse of the intertemporal elasticity of substitution. Households supply $\bar{L}$ units of labour inelastically in each period. The government is financed by households and the public sector net balance Gvt_t is rebated to their income balance. It affects the budget constraint whenever revenues from taxes differ from expenses on subsidies. Moreover, household savings are borrowed by firms to finance knowledge and physical capital investment. Households are also stakeholders in monopolistic firms and earn positive profits Π_{st}, for $s \in \{1, ..., N_c, m\}$, in each period because of the non-competitive market structure. The household budget constraint is:

$$B \equiv \sum_t p_{ct} C_t + \triangle A_T = \sum_t \left(w_t \bar{L}_t + Gvt_t \right) + \sum_t \left[\sum_j^{N_c} \Pi_{jt} + \Pi_{mt} \right], \tag{2}$$

$$\triangle A_T = P_{qT} q_T - P_{q0} q_0 + \sum_j \left(P_{HT,j} H_{T,j} - P_{H0,j} H_{0,j} \right) + P_{HT,m} H_{T,m} - P_{H0,m} H_{0,m},$$

$$Gvt_t = \tau_t p_{et} E_t - \sum_j s_{pc,jt} p_{jt} RD_{jt}^H - s_{pc,mt} p_{mt} RD_{mt}^H - s_{pr,t} p_{mt} RD_t^q,$$

where s_{pc} and s_{pr} are subsidies on process-related and product-related R&D investment, possibly differentiated by sector. Household savings $\triangle A_T$ are invested in all types of capital, which are then rented to firms. In each period, final consumption C_t is the aggregate demand for N_c sectoral consumption goods $C_{Y,jt}$ and it is specified as a Constant Elasticity of Substitution (CES) function:

$$C_t = \left(\sum_{j=1}^{N_c} \pi_j C_{Y,jt}^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}, \tag{3}$$

where π_j is a share parameter and ε is the elasticity of substitution between sectoral goods. The optimal demand for each sectoral good is the standard function of good j price:

$$C_{Y,jt} = \left(\pi_j \frac{p_{C,t}}{p_{jt}} \right)^{\varepsilon} C_t. \tag{4}$$

3.2 Production and Innovation

3.2.1 Consumption Good Producers

There are N_c firm types producing consumption goods and N_c is set exogenously. Markets have a monopolistic structure because of the innovation-based competition between firms. Within each sector firms share the same technology, i.e. the same input cost shares, but they can engage in process-related R&D activities to innovate and enhance their productivity. The firm with the best process-related technology is able to supply the good at the lowest price and secure a monopoly position in the market. In each period the market can be taken over by a competitor that successfully develops a process-related technology characterized by a higher knowledge capital content. The incentive for the incumbent monopolist to perform R&D activities comes from the possibility for entrants to substitute physical inputs for knowledge capital and supply a cheaper good, for given input prices and demand. The relatively higher technological level of entrant firms has been confirmed by empirical studies, for instance Linn (2008) for the case of energy intensity and Lentz and Mortensen (2008) for overall productivity. Notice that producers of consumption goods do not perform product innovation, so that relative differences in product characteristics across sectors are taken as given and cannot be changed through research. The j-th firm, $j = 1, ..., N_c$, manufactures consumption goods Y_{jt} with the multi-level CES technology using process-related knowledge H_{jt}, energy E_{jt}, labour L_{jt} and a bundle of energy-consuming physical capital K_{jt} , produced by the capital goods sector:

$$Y_{jt} = H_{jt}^{\gamma_j}\left[\eta_j(EE_{jt})^{\frac{\sigma_j-1}{\sigma_j}} + (1-\eta_j)VA_{jt}^{\frac{\sigma_j-1}{\sigma_j}}\right]^{\frac{\sigma_j(1-\gamma_j)}{\sigma_j-1}}, \tag{5}$$

$$VA_{jt} = K_{jt}^{\alpha_j}L_{jt}^{1-\alpha_j}, \tag{6}$$

$$EE_{jt} = \phi_{jt}E_{jt}, \tag{7}$$

where $EE_{jt}$is the composite of energy in efficiency units, given an index of energy productivity ϕ_t. Process-related R&D capital has decreasing marginal returns in production $(0 < \gamma_j < 1)$ and is combined with physical goods by Cobb-Douglas technology, as in previous studies, e.g. Goulder and Schneider (1999); Otto et al. (2008). The Cobb-Douglas specification ensures enough substitution between tangible and intangible goods and it is in line with the observed roughly constant share of R&D expenditures on gross domestic product in developed countries over the last thirty years (OECD, 2014). The stock of knowledge is sector-specific and it measures the broad variety of intangible assets that contribute to a firm's productivity. In many cases, in particular in the service sector, process innovation cannot be patented and the technology remains within the innovator's walls. The elasticity of substitution between energy and value added is assumed less than one, $0 < \sigma_j < 1$, following the empirical evidence, e.g. Hassler et al. (2012) and Baccianti (2013).

Capital good varieties The bundle of capital goods K_{jt} is an aggregation of various types of physical capital goods $k_{i,jt}$, $i \in [0,1]$, which comprises machines, equipments, vehicles and buildings. The physical capital stock in each sector j is defined as:

$$K_{jt} = \left(\int_0^1 k_{i,jt}^{\alpha_j} di \right)^{\frac{1}{\alpha_j}}. \tag{8}$$

The previous equation requires that the capital share α_j is a function of the elasticity of substitution between equipment varieties ν_j, as $\alpha_j = \frac{\nu_j - 1}{\nu_j}$. Moreover capital goods are substitutes, i.e. $\nu_j > 1$, which ensures the capital share α_j to be positive and less than unit. Each capital good variety is characterised by a level of quality that determines its embodied productivity. We adopt a specification commonly used in the literature of ISTC to define the effect of embodied technology on the production of the adopting firm. In each period firms decide the allocation of investment $m_{i,jt}$ for each type of capital i given information on q_{it}, the productivity of the specific type of machine, equipment or vehicle in the capital accumulation process:

$$k_{i,jt+1} = q_{it} m_{i,jt} + (1 - \delta_K) k_{i,jt}. \tag{9}$$

Capital k is measured in efficiency units: higher quality embodied in the investment good m leads to higher productivity.

An important feature of our model is to extend the capital vintage analysis from general capital productivity to energy productivity. All capital varieties are energy-consuming goods and in fact directly responsible for the energy consumed during production. Technical energy efficiency in production is a function of capital productivity, that is the technological level of each piece of capital employed by firms. We set the energy productivity indexϕ_{jt} of equations (5) - (7) to depend on the composition of capital varieties and vintages used by firms. The index ϕ_{jt} is defined as a weighted average of quality of capital installed,

$$\phi_{jt} = \int_0^1 \phi_{i,jt} \frac{M_{i,jt}}{M_{jt}} di, \tag{10}$$

where $M_{i,jt}$ is a measure of the physical stock of capital i installed up to time t and is defined as

$$M_{i,jt} = m_{i,jt} + \sum_{s=0}^{t-1} m_{i,js}(1-\delta_K)^{t-s}, \tag{11}$$

with $M_{i,j0}$, the initial stock of capital i. The energy efficiency of each capital type i installed is determined by

$$\phi_{i,jt+1} = q_{it}\frac{m_{i,jt}}{M_{i,jt}} + \phi_{i,jt}\left(1 - \frac{m_{i,jt}}{M_{i,jt}}\right). \tag{12}$$

The special feature of this model is endogenous energy efficiency, which is the third state variable in the firm's decision problem. Investment in fixed capital goods, $m_{i,jt}$, gives to the firm the possibility to improve its energy efficiency level in future periods if the current capital vintage has a higher embodied quality. In fact, energy efficiency $\phi_{i,jt}$ of a specific type of capital goods is determined by the composition of vintages installed over time and, clearly, the efficiency index $\phi_{i,jt}$ is not affected by investment if the quality of equipment and machines does not change over time. It is important to notice the twofold effect of capital-embodied technology. On the one hand higher capital productivity on the value added side is energy-using (given $\sigma_j < 1$, for all j) but, on the other hand, the bias of technology is counterbalanced by the energy-saving effect that as well characterises the results of innovation on capital goods.

Symmetric equilibrium We consider an equilibrium that features the same cost function for capital goods producers and $p^m_{it} = p^m_t$ for all i. Without heterogeneity in prices and quality of capital good varieties, in each sector firms have a symmetric allocation of capital across different types, that is $k_{i,jt} = k_{jt}$ for all j. As a result the bundle of capital goods K_{jt} is equal to k_{jt} and the average capital quality is equal to q_t. In symmetric equilibrium the level of energy efficiency (10) results to evolve as follows

$$\phi_{jt+1} = q_t\frac{m_{jt}}{M_{jt}} + \phi_{jt}\left(1 - \frac{m_{jt}}{M_{jt}}\right), \tag{13}$$

and the accumulation of sectoral capital K_t can be similarly rewritten as

$$K_{jt+1} = q_t m_{jt} + (1-\delta_K)K_{jt}. \tag{14}$$

Consumption goods producers maximize the flow of current and future profits in two steps. The allocation of production inputs is firstly set given market prices for labour, investment goods, energy and the cost of process-related R&D. At this stage the firm observes the quality of capital goods offered on the market and, given this piece of information, it decides upon investment in physical capital. The intertemporal profit maximization problem is:

$$\max_{\substack{H_{jt+1}, RD^H_{jt}, \phi_{jt+1} \\ E_{jt}, L_{jt}, m_{jt}, K_{jt+1},}} \Pi_j = \sum_{t=1}^{T} \beta^t \quad \{p_{jt}Y_{jt} - p_{jt}(1 - s_{j,pc})RD^H_{jt} - w_t L_{jt} - p_{Et}E_{jt} - p^m_t m_{jt}\} \tag{15}$$

$$\begin{aligned} \text{s.t.} \;\; Y_{jt} &= H^{\gamma_j}_{jt} \left[\eta_j (\phi_t E_{jt})^{\frac{\sigma_j - 1}{\sigma_j}} + (1 - \eta_j) VA^{\frac{\sigma_j - 1}{\sigma_j}}_{jt} \right]^{\frac{\sigma_j(1-\gamma_j)}{\sigma_j - 1}}, \\ K_{jt+1} &= q_t m_t + (1 - \delta_K) K_{jt}, \\ H_{jt+1} &= RD^H_{jt} + (1 - \delta_H) H_{jt}, \\ \phi_{jt+1} &= q_t \frac{m_{jt}}{M_{jt}} + \phi_{jt} \left(1 - \frac{m_{jt}}{M_{jt}} \right). \end{aligned}$$

where $\beta^t = \left(\frac{1}{1+\rho}\right)^t$ and $s_{j,pc}$ is the subsidy on R&D expenditures on process innovation. Process innovation decision is based on a couple of first order conditions on the optimal allocation of the process-related knowledge stock H_{jt+1} and R&D investment RD^H_{jt}:

$$p_{jt+1}\gamma_j \left(\frac{EVA_{jt+1}}{H_{jt+1}} \right)^{1-\gamma_j} + \lambda^H_{j,t+1}(1 - \delta_H) = \lambda^H_{j,t}, \quad \perp H_{jt+1} \tag{16}$$

$$\lambda_{j,t} = p_{jt}(1 - s_{j,pc}), \quad \perp RD^H_{jt} \tag{17}$$

where λ_{jt} is the multiplier associated with the capital accumulation constraint (14) and EVA_{jt} is a composite of energy, physical capital and labour, a subnest of (5). Investment and stock of physical capital are instead determined by the following first order conditions:

$$RMP^K_{jt+1} + \mu_{jt+1}(1 - \delta_K) = \mu_{jt}, \quad \perp K_{jt+1} \tag{18}$$

$$\mu_{jt} + \xi_{jt} \frac{(q_t - \phi_{jt})}{q_t} \left(\frac{1}{M_{j,t-1} \left(1 + \frac{m_{jt}}{M_{jt-1}} \right)^2} \right) = \frac{p^m_t}{q_t}, \quad \perp m_{jt} \tag{19}$$

$$P^{EVA}_{jt+1} \frac{\partial EVA_{jt+1}}{\partial \phi_{jt+1}} = \xi_{jt} - \xi_{jt+1} \left(1 - \frac{m_{jt+1}}{M_{jt+1}} \right), \quad \perp \phi_{jt+1} \tag{20}$$

where ξ_{jt} is the multiplier associated with the energy efficiency constraint (13) and RMP^K_{jt+1} is the revenue marginal productivity of physical capital in the next period. The firm chooses the optimal capital stock in efficiency units for the next period, K_{jt+1}, a decision that only focuses on the direct contribution of capital to production. Investment m_{jt} is instead measured in physical units and it has a secondary effect on energy efficiency. As equation (13) shows, physical units of current investment determine the weights of the latest vintage in the energy efficiency indicator of firms. If the current vintage has a different embodied efficiency q_t compared to the energy efficiency of installed capital ϕ_{jt}, then investment in a new vintage of physical capital allows to change the level of energy efficiency in production (equation 19).

Equation (20) sets the optimal level of energy efficiency in production. From the production function we derive the marginal productivity of one additional unit of energy efficiency, ϕ_t, that is

$$\frac{\partial EVA_{jt+1}}{\partial \phi_{jt+1}} = \left(p_{jt}^{EVA}\right)^{\sigma_j} EVA_{jt}\phi_{jt}^{\sigma_j-2} p_{Et}^{1-\sigma_j}.$$

The marginal productivity of energy efficiency is increasing in the price of energy, so that firms have higher incentives to install newer capital vintages as energy costs rise. Moreover, high volumes of physical production induce firms to employ a larger flow of energy in efficiency units and technological efficiency might be used to substitute for physical energy.

The optimal stock of physical capital is derived from the first order condition (18):

$$K_{jt+1} = \alpha_j \frac{P_{jt+1}^{VA} VA_{jt+1}}{\mu_{jt} - (1-\delta_K)\mu_{jt+1}}, \tag{21}$$

and the (shadow) price of physical capital stock results from (19),

$$\mu_{jt} = \frac{p_t^m}{q_t} - \xi_{jt} \frac{(q_t - \phi_t)}{q_t} \kappa\left(m_{jt}; M_{jt-1}\right), \tag{22}$$

by setting $\kappa\left(m_{jt}; M_{jt-1}\right) = \left(\frac{1}{M_{j,t-1}\left(1+\frac{m_{jt}}{M_{jt-1}}\right)^2}\right)$. The capital stock price μ_{jt} mainly depends on the price of investment goods, p_t^m, and it is adjusted to account for the energy-saving content of the latest vintage. We find the optimal demand for investment goods by using the law of motion (14) together with equations (21), (22) and (14):

$$m_{jt} = \frac{\alpha_j P_{jt+1}^{VA} VA_{jt+1}}{p_t^m - \xi_{jt}\left(q_t - \phi_{jt}\right)\kappa\left(m_{jt}; M_{jt-1}\right) - (1-\delta_K) q_t \mu_{jt+1}} - (1-\delta_K)\frac{K_{jt}}{q_t}. \tag{23}$$

Through optimization we get the cost function $c\left(R_{jt}^H, p_{Et}, w_t, p_t^m, q_t; \sigma_j, \alpha_j\right)$ to be used in the second stage together with household demand (4). Given isoelastic demand, the firm sets the standard monopolist price applying a constant markup on production costs:

$$p_{jt} = \frac{\varepsilon}{\varepsilon - 1} c\left(R^H_{jt}, p_{Et}, w_t, p^m_t, q_t; \sigma_j, \alpha_j\right). \tag{24}$$

3.2.2 Production of Capital Goods

Capital good varieties are produced by firms in a separate sector and the mass of all varieties is assumed to be unit. The possibility to engage in both product-related and process-related R&D is a special feature of this sector. Capital good producers can change the quality of their product through product innovation. Also in this case a non-competitive market structure arises because of innovation. The successful monopolist in the market for a single capital variety is able to supply a product with the best combination of low cost and high quality, compared to competitors. We assume for simplicity that producers of different capital varieties share the same multi-level CES technology in producing capital varieties, Y^m_{it}:

$$Y^m_{it} = H^{\gamma_m}_{m,it} \left[\eta_m E^{\frac{\sigma_m - 1}{\sigma_m}}_{m,it} + (1 - \eta_m) L^{\frac{\sigma_m - 1}{\sigma_m}}_{m,it}\right]^{\frac{\sigma_m(1-\gamma_m)}{\sigma_m - 1}} \tag{25}$$

using process-related knowledge capital $H_{m,it}$, energy $E_{m,it}$ and labour $L_{m,it}$. In order to simplify calculations, the firm in this sector does not employ its own products in production but only in the accumulation of product-related and process-related knowledge. As before, R&D activities employ labour and energy similarly to production activities and the investment in product or process innovation requires the use of one unit of sectoral output Y^m_{it}. Demand for capital goods originates from investment in all consumption goods sectors. As a result, the total demand faced by producer i in every period is:

$$D^m_{it} = \sum_{j \in \{1,\ldots,J\}} m_{i,jt}. \tag{26}$$

The demand for the specific variety of investment good m_{jt} can be derived similarly to equation (23), but without imposing the symmetric equilibrium. The law of motion of the capital stock (9) together with the demand for the stock of capital variety i,

$$k_{i,jt+1} = \left(\frac{P^K_{jt}}{p^K_{i,jt}}\right)^{\nu_j} K_{jt+1}, \tag{27}$$

with $P^K_{jt} = \left[\int_0^1 \left(p^K_{i,jt}\right)^{1-\nu_j} di\right]^{\frac{1}{1-\nu_j}}$ and $p^K_{i,jt} = \mu_{i,jt} - (1 - \delta_K)\mu_{i,jt+1}$, gives

$$m_{i,jt} = \left(\frac{P^K_{jt}}{\chi_{i,jt}}\right)^{\nu_j} q_{it}^{\nu_j - 1} K_{jt+1} - (1-\delta_K)\frac{k_{i,jt}}{q_{it}}, \tag{28}$$

where $\chi_{i,jt} = q_{it}p^K_{i,jt} = p^m_{it} - \xi_{i,jt}(q_{it} - \phi_{i,jt})\,\kappa\,(m_{i,jt}; M_{i,jt-1}) - (1-\delta_K)q_{it}\mu_{i,jt+1}$.

Equation (28) shows the difference between product and process innovation: the former shifts the product demand curve whereas the latter aims to increase demand through a lower price p^m_{it} (in $\chi_{i,jt}$), leaving the demand schedule unchanged. The increase in product-embodied quality q_{it} changes the customers' willingness to pay for the piece of capital variety, a standard result in models with innovation along the quality ladder, e.g. Aghion and Howitt (1992). There are three major effects at work. The current vintage of investment goods become more productive with respect to the installed capital stock, which gets depreciated further by q_{it} in terms of effective units. The effect is straightforward to see for the special case of $k_{i,jt} = q_{it-1}m_{it-1}$, in which product innovation depreciates the level of effective productivity of previous capital vintages by a factor $\frac{q_{it-1}}{q_{it}}$. The other two effects are in the first term of equation (28). First, the indirect effect of energy efficiency on the effective cost of a new capital vintage is captured by $\chi_{i,jt}$. Second, a more productive investment good variety has a competitive advantage with respect to other varieties and there is a positive effect on demand $m_{i,jt}$ because of substitution, as $\nu_j > 1$. More precisely, the effect of quality on the optimal investment in physical capital is

$$\frac{\partial m_{i,jt}}{\partial q_{it}} = \left[(\nu_j - 1)\left(\frac{1}{q_{it}}\right)^{2-\nu_j}\left(\frac{1}{\chi_{i,jt}}\right)^{\nu_j} + \nu_j\left(-\frac{\partial \chi_{i,jt}}{\partial q_{it}}\right)\left(\frac{1}{\chi_{i,jt}}\right)^{1+\nu_j} q_{it}^{\nu_j - 1}\right]\left(P^K_{jt}\right)^{\nu_j} K_{jt+1} + \tag{29}$$

$$+(1-\delta_K)\frac{k_{i,jt}}{q_{it}^2} > 0,$$

with $\frac{\partial \chi_{i,jt}}{\partial q_{it}} < 0$. Equation (29) clearly indicates that the impact of capital quality on investment demand is positive and capital good producers might foster the purchase of new capital goods by performing product innovation. Besides direct capital productivity, energy efficiency is a second channel to influence investment decisions through product quality changes. Notice that each firm i is too small to affect the average price P^K_{jt} and use of capital K_{jt+1} in sector j. Nevertheless the investment in product-related R&D by all producers of capital varieties might have a twofold demand externality. Generalized quality improvements not only lead to an increase in the sector j stock of physical capital in effective units, but they as well lead to an increase in average energy efficiency ϕ. Under complementarity between energy and value added, higher energy-saving technology rises the demand for physical capital.

Similarly to the consumption goods producers, the firm maximises profits in two stages, minimising production costs first and then choosing the optimal product price together with investment in knowledge capital. In the first stage of profit maximization the firm performs cost minimization and sets the optimal demand of labour, energy, as well as process innovation:

$$\begin{aligned}
\max_{H_{m,it+1}, RD^H_{m,it}, L_{m,it}, E_{m,it}} \Pi_{it} &= \sum_{t=1}^{T} \beta^t \quad \left\{ p^m_{it} \left[Y^m_{it} - (1 - s_{m,pc}) RD^H_{m,it} \right] - w_t L_{m,it} - p_{Et} E_{m,it} \right\} \\
\text{s.t. } H_{m,it+1} &= RD^H_{m,it} + (1 - \delta_H) H_{m,it},
\end{aligned} \tag{30}$$

and subject to (25). The parameter $s_{m,pc}$ is the subsidy on R&D expenditures on process innovation, equal across firms $i \in [0, 1]$. Production costs are constant across i, which justifies the symmetric equilibrium condition used in the previous section. Factor demands are derived from the following first order conditions:

$$p^m_t \frac{\partial Y^m_{it}}{\partial L_{m,it}} = w_t \quad \perp L_{m,it}, \tag{31}$$

$$p^m_t \frac{\partial Y^m_{it}}{\partial E_{m,it}} = p_{Et}, \quad \perp E_{m,it}, \tag{32}$$

$$(1 - s_{j,pc}) p^m_{it} = \lambda^m_{it} \quad \perp RD^H_{m,it}, \tag{33}$$

$$p^m_{t+1} \frac{\partial Y^m_{it+1}}{\partial H_{m,it+1}} + (1 - \delta_H) \lambda^m_{it+1} = \lambda^m_{it} \quad \perp H_{m,it+1}. \tag{34}$$

After minimizing costs with respect to process-related knowledge capital and physical inputs, the firm sets the product price and the level of quality of capital goods sold in that period. By using the cost function $c(R^H_{m,it}, w_t, p_{Et}; \sigma_m, \gamma_m)$ derived in the first step, the second step is the following profit maximization problem:

$$\max_{p^m_{it},RD^q_{it},q_{it}} \Pi_{it} = \sum_{t=1}^T \beta^t \quad \{[p^m_{it} - c(.)]\, D^m_{it} - (1 - s_{m,pr})c(.)RD^q_{it}\}$$

$$\text{s.t.} \qquad D^m_{it} = \sum_{j \in \{1,\dots,J\}} m_{i,jt} \tag{35}$$

$$q_{it} = \left(\frac{RD^q_{it}}{q_{it}}\right)^{\psi} + (1 - \delta_q)q_{it-1}, \tag{36}$$

$$q_{i0} = q_i^{init}. \tag{37}$$

where $q_i^{init} > 0$ is a positive initial level of quality, $d_q$is a scaling parameter and $0 < \psi \leq 1$ sets the degree of marginal return of R&D investment in the development of higher quality products. The subsidy $s_{m,pr}$ is applied on R&D expenditures on product innovation. First order conditions:

$$D^m_{it} + [p^m_{it} - c(.)] \sum_j \frac{\partial m_{i,jt}}{\partial p^m_{it}} = 0, \quad \perp p^m_{it} \tag{38}$$

$$(1 - s_{pr})c(.) = \frac{\vartheta_{it}}{q_{it}} \psi \left(\frac{RD^q_{it}}{q_{it}}\right)^{\psi - 1}, \quad \perp RD^q_{it} \tag{39}$$

$$[p^m_{it} - c(.)] \sum_j \frac{\partial m_{i,jt}}{\partial q_{it}} + \vartheta_{it+1}(1 - \delta_q) = \vartheta_{it} \left[1 + \left(\frac{RD^q_{it}}{q_{it}}\right)^{\psi} \frac{\psi}{q_{it}}\right], \quad \perp q_{it} \tag{40}$$

where ϑ_{it} is the multiplier associated to the quality accumulation constraint (36). Equation (40) sets the optimal level of product quality at time t, given the impact of quality on investment demand (29). Equation (38) determines the optimal price set by the monopolist firm. In this case a single producer is selling to multiple buyers, charging a unique price because price differentiation is not possible. As a result the pricing formula is slightly more complex than the previous case because buyers - i.e. sectors - differ with respect to their elasticity of demand for capital goods:

$$p^m_{it} \left(1 + \frac{1}{\sum_j \theta_{i,jt} \varrho_j}\right) = c(.), \tag{41}$$

where $\theta_{i,jt} = \frac{m_{i,jt}}{\sum_j m_{i,jt}}$ is the share of product i sold to sector j at time t and the coefficient $\varrho_j = \frac{\partial m_{i,jt}}{\partial p^m_{it}} \frac{p^m_{it}}{m_{i,jt}}$ is the elasticity of demand for i in sector j .

3.2.3 Energy Sector

Energy is produced by a specialized sector that employes labour using a linear technology:

$$E_t = a_E L_{Et}. \tag{42}$$

The market for energy is perfectly competitive and energy firms supply energy services to the rest of the economy, including consumption good sectors and capital good producers. The profit maximization problem for the utility firm is:

$$\begin{aligned} \underset{E_t}{max} \quad \Pi_t^E = & \quad p_{Et}(1-\tau_E)E_t - w_t L_{Et} \\ s.t. \qquad\quad & \quad (42) \end{aligned}$$

where τ_E is the energy tax imposed by the government.

3.3 Equilibrium

The general equilibrium is specified by series of prices and quantities that satisfy all model equations, that is market clearing conditions for all goods and input factors, as well as zero profit conditions and the budget constraint. The analytical solution of the model is found[3] by imposing a balanced growth path in which variables grow at constant rates, even if not necessarily equal. In fact, capital-embodied productivity affects consumption goods firms heterogeneously. The innovation process is centralized in the investment good sector and all consumption good producers face the same development path of capital technologies over time. Yet, the adoption of newest vintages differs across sectors because of heterogeneity in energy and capital shares and the actual contribution of investment-embodied productivity growth to sectoral output growth differs across consumption good sectors. As a result, our benchmark growth rates differ across sectors. Whereas unbalanced growth in other models (cf. Herrendorf et al., 2014) originates from differences in sectoral Hicks neutral technological progress, i.e. TFP, in our model the impact of technological progress on sectoral production is partly factor-augmenting.

The growth rate of output in a consumption good sector j has to be equal to the growth rate of demand, which includes demand for final consumption and for investment in knowledge capital:

$$g_j = \varpi_j g_j^C + (1-\varpi_j) g_j^{RDh},$$

where ϖ_j is the benchmark share of consumption on good j's demand. We set process-

[3]Further details including the calculation of the benchmark growth path are available from the authors upon request.

related R&D investment to grow at the same rate of output growth g_j, so that $g_j^{RDh} = g_j$. The heterogeneous impact of quality growth g^q on sectoral prices is the main reason for g_j to differ across js. In fact, the growth in demand for a consumption good j

$$g_j^C = \varepsilon(g^{PC} - g_j^{PY}) + g_C,$$

depends on changes in the relative price of consumption. Investment-specific technological change g^q has a direct effect on the cost of both energy and capital, but not necessarily in the same way across sectors and $g_{j_1}^{PY}(g^q; \alpha_{j_1}, \eta_{j_1}) \neq g_{j_2}^{PY}(g^q; \alpha_{j_2}, \eta_{j_2})$ if $\alpha_{j_1} \neq \alpha_{j_2}$or $\eta_{j_1} \neq \eta_{j_2}$ for any $j_1 \neq j_2$, with $j_1, j_2 \in J$. For the special case of no growth in capital quality, g^q, the economy follows a balanced growth path with $g_j = g_C$ for all $j \in J$.

In the investment good sector, part of the demand comes from investment in product-related and process-related R&D expenditures and the rest is investment demand from consumption good sectors. Market clearing and the assumption that $g_m^{RDH} = g_m$ implies that the growth rate in the production of investment goods, g_m, is

$$g_m = \sum_j \frac{\varpi_m^j}{1 - \varpi_m^H} g_j^m(g^q, g_j; \alpha_j, \sigma_j) + \frac{1 - \sum_j \varpi_m^j - \varpi_m^H}{1 - \varpi_m^H} \left(\frac{1 + \psi}{\psi} \right) g^q,$$

given benchmark demand shares ϖ_m^h, with $h \in \{1, ..., J, H\}$ and the balanced growth path condition on quality growth imposed on (36).

By using the first order condition for product innovation (39), the growth rate of quality in balance growth is $g^q = \psi(g_m^\vartheta - g_m^P)$. Equation (40) requires the growth in the shadow price of the quality stock g_m^ϑ to grow as much as the marginal revenue productivity of quality. The pair g^q and g_m^ϑ can be found by solving the following system:

$$\begin{array}{lcl} g^q & = & \psi(g_m^\vartheta - g_m^P) \\ g_m^\vartheta & = g_m^P + \sum_j \theta_j^m & \left[\Lambda_j \left(g_j^\xi - g_j^\mu \right) + \left(g_j^m - g^q \right) \right] \end{array}$$

where $g_j^\xi - g_j^\mu = v_j \left(g_j^\xi - g_m^P + g^q \right)$. Λ_j and v_j are parameters that are function of benchmark values of $\kappa(.), \mu$ and ξ. The coefficient θ_j^m is the benchmark share of investment good demanded by sector j . It results that

$$
\begin{aligned}
g_m^{\vartheta} &= g^P + \frac{g^q}{\psi}, \\
g^q &= \frac{1 + \sum_j \theta_j^m \Lambda_j \upsilon_j}{\left(\frac{1+\psi}{\psi} - \sum_j \theta_j^m \left(\Lambda_j \upsilon_j \varsigma_j + \Delta_j\right)\right)} g,
\end{aligned}
$$

where g and g^P are respectively the baseline growth rates of aggregate consumption and of labour and energy prices. The coefficient ς_j also depends on underlying structural parameters and it results that $\varsigma_j < 0$, which leads to $g^q < g$. The result can be explained by the characteristic shape of the innovation possibility frontier of product innovation (36). The effectiveness of product-related R&D investment declines as the quality stock increases and there are additional decreasing returns due to $\psi < 1$.

4 Extended CGE Version and Calibration

The model presented in the previous section is extended to include additional features like international trade and sectoral intermediate goods use. The resulting CGE model provides a more detailed representation of the economy and it is employed for carrying out policy simulations. First of all, the input-output structure of production is a fundamental characteristic of multisector economies. The fact that consumption goods are used in the production process of all other sectors, including capital good and energy production, introduces stronger connections between production units and amplifies the impact of external shocks. The main data used for model calibration is the input-output table (or Social Accounting Matrix, SAM) of the EU 27 country block for year 2008, constructed by Eurostat. Data are disaggregated up to 65 subsectors, according to the NACE Rev. 2 classification. We consider the whole EU 27 aggregate and do not account for cross-country flows within the block, because of the complexities in representing the within-Europe flows of research funding and spillover effects. European countries have in fact strongly interconnected research networks. The average share of public research funding from EU or EU-national sources that supports transnational research within the European Union has been estimated to be 3.8% in 2010 (European Commission and Eurostat, 2012). By adding cross-country flows of private business R&D expenditures into the picture, it results a strong interdependence of member states with respect to R&D activities (see for instance Dachs et al. (2012) for more detailed statistics).

The SAM is the main data source to calibrate factor share parameters in production as well as share coefficients on the demand side, specifying the allocation of output among alternative destinations in equilibrium. We need first to rearrange the original SAM and make it consistent with the model assumptions. For instance, output of the capital good sector is only demanded by consumption good producers as investment goods, not intermediates, in the model. The row in the SAM has to be adjusted accordingly. The next step is to integrate information about R&D investment into the data matrix.

4.1 Integrate R&D Expenditures in the SAM

The SAM for the EU27 has detailed information about sectoral production and demand, in particular the input-output structure of flow of intermediate good use across sectors. The construction of these data is still based on the ESA 1995 standard and R&D expenditures are accounted as intermediate consumption, rather than gross fixed capital formation as in the new ESA 2010. That is, the original SAM is inconsistent with our model because innovation expenditures do not make a positive contribution to gross domestic product, which are instead regarded as investment in our model. The issue is not novel in the field of R&D-based CGE modelling and we follow previous studies with respect to modifying the SAM to have a consistent model calibration, i.e. Otto et al. (2008); Löschel and Otto (2009).

Data for R&D expenditures by sector are obtained from OECD ANBERD database for year 2008, with values converted into millions of euros and expressed in current prices. The dataset is a unique data source for international business R&D, with fine sectoral disaggregation and highly harmonized cross-country data expressed also in purchasing power parity units. A disadvantage of the ANBERD database is the limited coverage: not all EU27 countries are included but only [4] the largest economies, accounting for 90 % of total R&D expenditures in the EU27 area (European Commission and Eurostat, 2012). It is important to split the R&D statistics into values relative to product and process innovation. The ANBERD database does not provide information on the composition of R&D expenditures with respect to the type of innovation. We rely on the results of the Community Information Survey (CIS) to retrieve information useful to partition the R&D aggregates into product and process innovation expenditures. In particular, we rely on the CIS data statistics provided by the Eurostat website in order to have the complete collection of results for all countries. The CIS contains data on the fraction of firms that perform any type of innovation, as well as the the share of firms that engage in specific innovation activities. The database does not have a direct measure of the share of R&D expenditures dedicated to process and product innovation separately. Nevertheless, among all innovative firms in the sample I we have a set of firms that perform only product innovation, $I_{pc}^{only} \subseteq I$, only process innovation, $I_{pr}^{only} \subseteq I$,

[4]Including Austria, Belgium, Czech Republic, Estonia, Finland, France, Germany, Hungary, Italy, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, United Kingdom and Romania.

and a group of firms that do both innovation activities, $I^{both} \subseteq I$. Call θ_{pc}^{only} and θ_{pr}^{only} the shares of firms doing only process and product innovation, respectively. The share of firms doing both activities is instead θ^{both} and it should be that $\theta_{pc}^{only} + \theta_{pr}^{only} + \theta^{both} = 1$.

Then

$$RD_{TOT} = \sum_{i \in I_{pc}^{only}} RD_i + \sum_{i \in I_{pr}^{only}} RD_i + \sum_{i \in I^{both}} RD_i,$$

by assuming that the total (or average) R&D investment spent by a single firm does not vary across different innovation groups, i.e. $RD_i = \bar{RD}, \forall i \in I$,

$$n\,\bar{RD} = n_{pc}\bar{RD} + n_{pr}\bar{RD} + n_{both}(\alpha_{pc}\bar{RD} + (1-\alpha_{pc})\bar{RD}),$$

with $\alpha_{pc} \in [0,1]$. If the fraction of process-related R&D expenditures at the aggregate level is equal to the process innovation share α_{pc} for firms performing both types of R&D, we have

$$\alpha_{pc} = \theta_{pc}^{only} + \alpha_{pc}\theta^{both},$$

$$\alpha_{pc} = \frac{\theta_{pc}^{only}}{1-\theta^{both}}.$$

We find that in the investment good sector about 78 % of R&D expenditures are dedicated to product innovation, a much higher value compared to the product-R&D share of other sectors (57%).

Production and innovation data are aggregated up to the seven macrosectors used in the model: five consumption good sectors, i.e. *Agriculture* (AGR), *Energy Intensive Manufacturing* (EIM), *Low Energy Intensity Manufacturing* (NEIM), *Transport and Trade* (TrTr) and *Services* (SERV), together with the capital good sector and the energy sector. The capital good sector includes the production of machinery, equipment, vehicles and buildings. The energy sector is calibrated using data for both electricity production and supply of fuels and materials. A key feature in the model is that physical capital uses products from the energy sector. As we do not differentiate between different types of capital and we keep a broad level of aggregation, the energy sector covers the supply of a large range of natural resources, not only energy but as well raw materials. Product innovation on capital goods improves the general efficiency in using natural resources. An important issue in the aggregation process is related to differences in data sources. The ANBERD database is constructed using the ISIC rev. 4 sectoral classification, whereas the SAM groups firms according to the NACE rev. 2 standards. Data aggregation starting from the finest available level of disaggregation of the original datasets allows to reduce discrepancies between the R&D aggregates and the aggregated SAM due to the different sectoral classifications.

Once data are aggregated, we proceed to integrate R&D expenditure data into the SAM. The reclassification of R&D expenditures into investment in knowledge capital entails the creation of a new endowment, the introduction of a new row of factor compensation and the need of cleaning up the SAM from potential double counting. R&D expenditure data are regarded as fixed capital formation, i.e. intangibles, and enter the SAM as a new column. R&D activities are assumed to trade domestically and there is no import or exports of knowledge investment. Knowledge capital generates in each year a flow of compensation for R&D services that needs to be computed. There are no data available but an approximation can be calculated assuming the economy to be in balanced growth. Given the depreciation rate for knowledge and growth rates of sectoral output, the flow of R&D rent is calculated using the optimal conditions (16), (34) and (40), together with the balanced growth level of investment obtained from the law of motions of each capital stock. For process innovation, the compensation for R&D services of the sector-specific knowledge stock is given by the formula

$$Rent_H^{R\&D} = RH_0 \frac{Inv_H^{R\&D}}{\delta_H + g},$$

where RH_o is the benchmark value for the rental rate of process-related knowledge capital and g is the growth rate of output in that sector. For product innovation, the flow of R&D compensation is instead calculated as

$$Rent_q^{R\&D} = Rq_0 \left(\frac{(1+g^q)^{1+\psi}}{\delta_q + g^q} \right)^{\frac{1}{\psi}} \left(Inv_q^{R\&D} \right)^{\frac{\psi}{1+\psi}},$$

where Rq_0 is the benchmark value for the rental rate of product-related knowledge capital and g^q is the balanced growth rate of the product quality stock.

The necessary adjustment for the SAM to be balanced again is carried out following the procedure used in Otto et al. (2008), which basically debits the R&D investment value to the intermediate consumption columns according to their original shares and finally requires to adjust the supply side for it to match total demand.

4.2 Model Calibration

We express the model in calibrated share form and follow a standard calibration procedure. Data for the base year are used as reference for setting benchmark values of all share pa-

Parameter	Description	Value	Parameter	Description	Value
σ_j	elasticity between energy and VA	[.1 - .3]	$\sigma_{top,j}$	Elasticity between intermediates and K-L-E	[.2 - .5.]
σ_A	Armington elasticity (j, m, E)	1.4	ε	elasticity between sectoral goods in final demand	2
$\sigma_{In,j}$	Elasticity between intermediates	[.05 - .25]	ψ	Productivity of product-R&D	.9
$\sigma_{In,m}$	Elasticity between intermediates	.25	γ_j	Cost share of knowledge	[.001 - .014]
$\sigma_{In,E}$	Elasticity between intermediates	.25	γ_m	Cost share of knowledge	.004
$\sigma_{top,E}$	Elasticity between intermediates and labour	.6	δ_H	depreciation - knowledge capital	.2
σ_m	elasticity between labour and energy	.2	δ_q	depreciation - quality	.2
$\sigma_{top,m}$	Elasticity between intermediates and L-E	.5	δ_K	depreciation - physical capital	.05

Table 1: Model parameters: Calibration

rameters in production functions and final demand. We refer to previous studies (Otto et al. 2008 and Baccianti 2013) for calibrating the elasticities of substitution of production and utility functions. Physical and knowledge capitals are characterized by a different process of depreciation, an intuitive argument that has been confirmed by empirical work (e.g. Mead 2007 and Hall 2010). Depreciation rates of physical capital for all consumption good sectors are set to 5 percent, whereas the knowledge stock depreciates faster, at a rate of 20 percent in all sectors and equally for product-related and process-related knowledge.

Sectoral production functions use energy in efficiency units but only physical units of products from the energy sector are available in the data. We introduce a scaling coefficient b_j in the law of motion of energy efficiency ϕ_{jt} (equation 13) and calibrate the parameter in a way to have a level of ϕ equal to one in the benchmark year. The modified equation for the dynamics of energy efficiency is $\phi_{jt+1} = b_j q_t \frac{m_{jt}}{M_{jt}} + \phi_{jt}\left(1 - \frac{m_{jt}}{M_{jt}}\right)$.

The model is defined over an finite horizon, which arises the issue of terminal capital stocks. We follow (Lau et al., 2002) and introduce post-terminal stock quantities, with their associated price. Post-terminal variables are set by imposing endogenous balanced growth conditions.

5 Environmental and Research Policies: Some Results

We carry out a set of simulation exercises to assess a wide range of policy instruments, covering both innovation and environmental policy. The time horizon is year 2050.

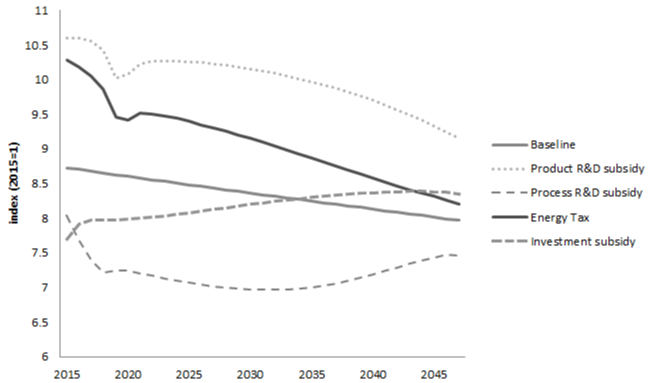

Figure 1: Ratio of product R&D to process R&D in the capital good sector.

5.1 R&D subsidies

Product R&D subsidy We study the effect of innovation subsidies, a form of governmental support to R&D investment in percentage of research costs (including staff and necessary structures). In this section we discuss the results related to the introduction of a 15% R&D subsidy on product innovation in the capital good sector.

The subsidy increases the quality of produced capital goods and accelerates capital accumulation. With higher quality, investment in physical capital becomes more appealing and the capital stock in effective units rises. In the capital good sector R&D activities are, not surprisingly, turned to research on product innovation. The ratio of investment in product-related R&D to the one in process-related R&D is up by 9% with respect to the baseline in the long run (Figure 1). The subsidy on product innovation is very effective in changing innovation profitability for durable good producers, taking into account that in the no policy case research would otherwise be redirected towards process innovation. Figure 2 shows that higher quality of existing capital goods does not induce firms in consumption good sectors to reduce the pace of knowledge accumulation. After a short term decline due to a drop in demand of sectoral goods (Figure 4), in-house R&D picks up and firm accelerate the accumulation of knowledge driven by the expansionary effect of higher capital productivity. This outcome, similarly to other results below, suggest that the market size effect is crucial in the model for the decision to engage in process innovation.

The short-run decline in consumption might be explained by intertemporal optimization:

Product R&D subsidy (15%)	Process R&D subsidy (15%)	Energy Tax (25%)	Investment Subsidy (20%)
2.26	-2.74	-4.30	-3.89

Table 2: Welfare impact of policies

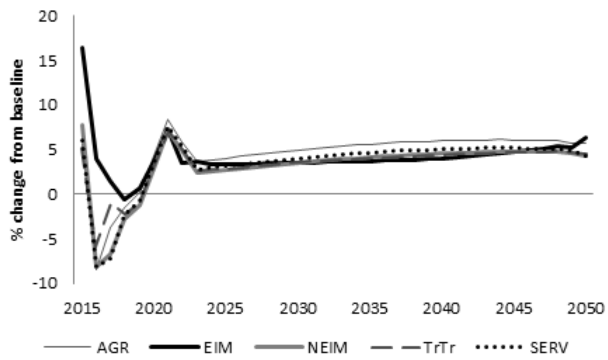

Figure 2: Impact of a product innovation subsidy on process innovation

agents take chance to invest in higher quality capital by postponing investment. In the short run production in consumption good sectors decline, with the exception of energy-intensive industries. The reason is related to the underlying input-output structure. The capital good sector makes heavy use of intermediates from energy-intensive firms and, for the EIM sector, the lower final demand is mitigated by soaring production in that sector. The overall impact on aggregate welfare - the discounted stream of consumption up to 2050 - results to be positive, close to 2.3 % (Table 2).

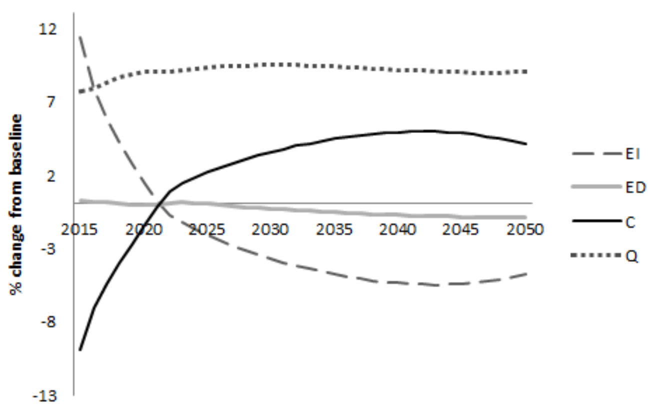

Figure 3: Macroeconomic impact of a product innovation subsidy

Note: EI: energy intensity; ED: energy demand; C: aggregate consumption; Q: quality stock of capital goods.

A product innovation subsidy is a quite powerful instrument to promote energy efficiency. Fig. 5 shows that the energy efficiency indicator ϕ jumps by more than 8% in all consumption good sectors, which is due to a combination of higher replacement rate of old capital vintages and a better quality of available technologies. This energy efficiency indicator only measures the energy efficiency embodied in the installed capital goods and does not take into account additional productivity gains from the accumulation of knowledge. Looking instead at the aggregate energy intensity, we observe a positive overall outcome for this policy. Figure 3 reveals the tendency for aggregate energy intensity of final consumption to decline over time and to achieve a 5% improvement with respect to the no intervention scenario. The policy slows down the growth in total energy demand and makes it decouple from aggregate consumption, but it has little success to reduce the absolute amount of energy used in the economy.

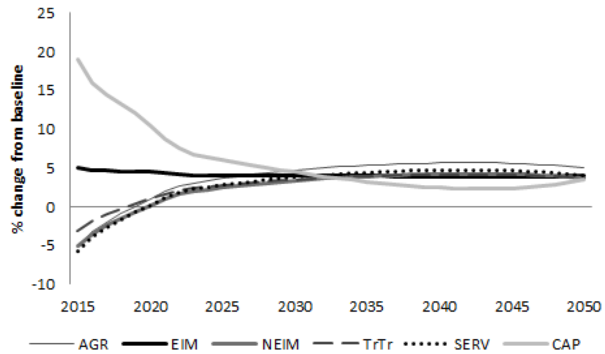

Figure 4: Impact of a product innovation subsidy on sectoral output

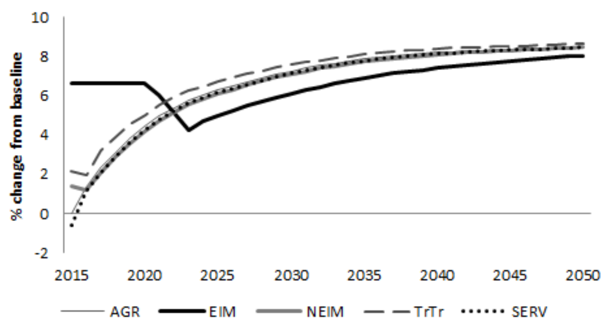

Figure 5: Impact of a product innovation subsidy on energy efficiency of the stock of durable goods

Process R&D subsidy The subsidy to process innovation is applied uniformly to all sectors engaged in process-related R&D and, compared to the other innovation subsidy, this instrument directly involves a larger group of innovation centres (knowledge is sector-specific). The subsidy triggers an immediate push in R&D investment in process innovation and, in turn, higher R&D investment has a positive impact on sectoral output in the short run (Fig. 8). In the long run the positive effect on process innovation subdues and process-related R&D investment results to be in all consumption good sectors about 9-10% higher than in the baseline (Fig. 6). Similarly, the capital good sector experiences a stronger accumulation of knowledge capital and the research effort is substantially turned towards process innovation (Fig. 1).

Process innovation is input saving and demand for energy declines, along with demand for investment goods. The depressed condition in the market for capital goods leads to a scaling down in R&D investment on product quality (Fig. 7). The level of quality of investment goods stays low even after the demand for capital catches up. In this scenario capital goods are cheaper but with lower embodied quality, which is important for both economic growth and environmental concerns. Production in all sectors is much more capital-intensive than knowledge-intensive and a process R&D subsidy is less effective to boost aggregate consumption and reduce energy consumption. Moreover, firms are accumulating capital with lower embodied productivity compared to the baseline and energy intensity tends to deteriorate over time, leading to an increase in the growth of energy demand in the last periods. Figure 9 shows that the energy efficiency of the capital stock is lower in some consumption good sectors and, in general, it deteriorates over time because of the accumulation effect: capital with worse quality (compared to the no policy scenario) has been installed since the introduction of the policy.

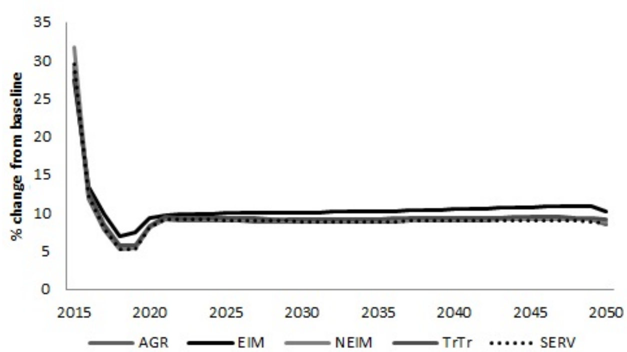

Figure 6: Impact of a process innovation subsidy on process innovation

5.2 Environmental policy - Energy Tax

We simulate the impact of a 25% proportional tax on the energy price, that might be introduced for environmental reasons. This scenario can as well be a rough representation of carbon pricing applied to the energy sector, neglecting the possibility of switching between different energy sources. The energy tax is very effective to reduce energy demand: the growth of aggregate energy production drops by 7.8% as soon as the tax is introduced and does not recover in the long run. The strong effect is the combination of a scale and technology effect. In the short run aggregate consumption falls by 10% and the quality of

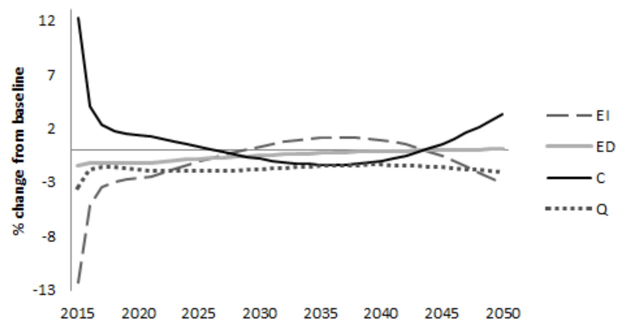

Figure 7: Macroeconomic impact of a process innovation subsidy

Note: EI: energy intensity; ED: energy demand; C: aggregate consumption; Q: quality stock of capital goods.

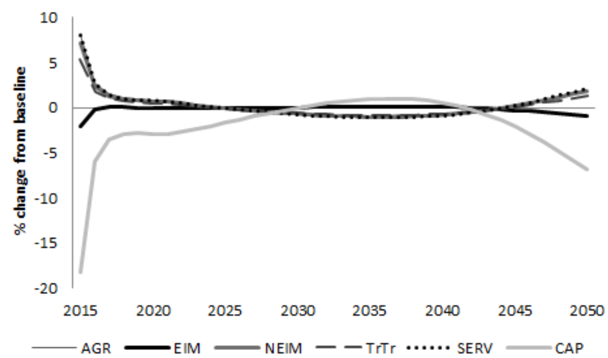

Figure 8: Impact of a process innovation subsidy on sectoral output

capital goods promptly reacts to the higher energy costs, going up by 4-5%. Over time final consumption recovers, whereas the energy efficiency of newly produced capital goods grows at a slower pace.

At the sectoral level, production drops in all consumption good sectors (Fig. 12). Agriculture (AGR) and lighter industrial productions (NEIM) experience the heaviest losses, by approximately 4.5% in the long term. Once more, the input-output structure of the model generates a quite surprising result. The drop in output for the energy intensive sector is quite modest, and it is because the capital good sector is benefiting from the tax. This results suggest that there might a trade-off between environmental and innovation goals.

Finally, results show no sign of a significant rebound effect from capital production. The higher level of production in the durable good sector does not have a noteworthy effect on aggregate energy demand.

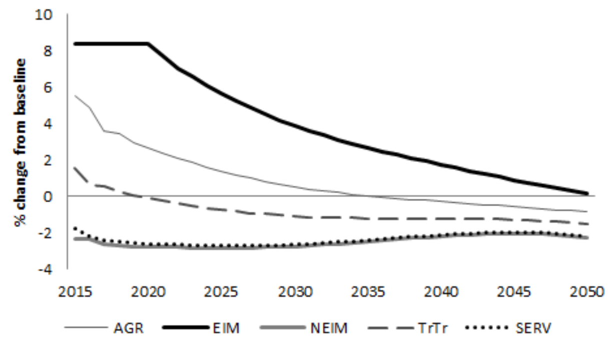

Figure 9: Impact of a process innovation subsidy on energy efficiency of the stock of durable goods

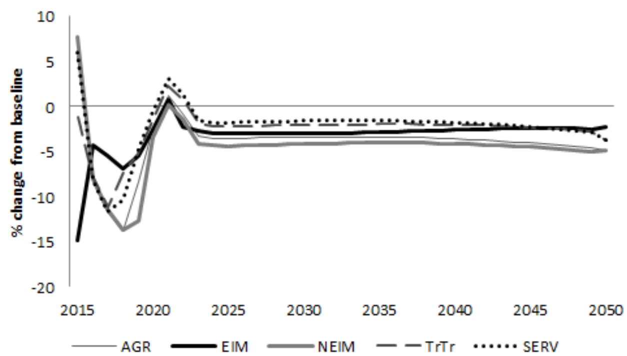

Figure 10: Impact of an energy tax on process innovation

5.3 Demand pull policy

Finally we consider a subsidy for the investment in new vintages of physical capital goods. The subsidy applies to the cost of investing in physical capital in consumption good sectors. The policy clearly triggers higher capital investment and it has an expansionary effect on the production of durable goods in the long term (Fig. 16). Even if capital investment is accelerated, R&D on product quality takes time to increase and the equilibrium quality stock slowly rises with respect to the baseline. Figure 1 shows that the subsidy initially favours cost-cutting innovation on durable goods but the effect is reverted in the long run. Therefore in the earlier phase, energy efficiency of the installed capital stock (Fig. 17) tends to rise because of the higher rate of replacement of capital vintages. Later on the trend continues, but mostly because of the higher embodied quality of physical capital in the last phase.

Faster capital accumulation substitutes out energy in production and, together with the capital vintage replacement effect, it contributes to lower energy demand. But this is not the fully story. Energy intensity actually increases with respect to the baseline (Fig. 15) and the policy seems to fail in leading the economy towards sustainable development. The drop in energy demand is instead driven by a fall in aggregate consumption, which is accompanied

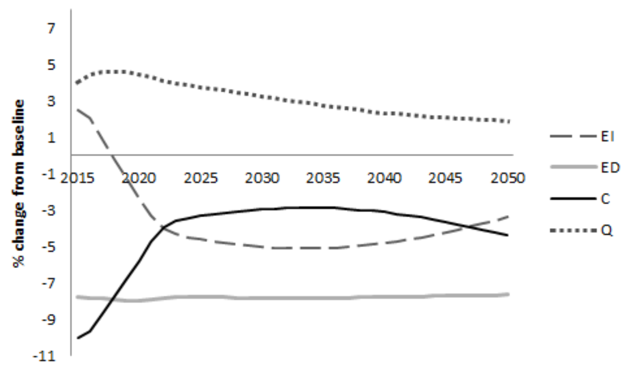

Figure 11: Macroeconomic impact of an energy tax

Note: EI: energy intensity; ED: energy demand; C: aggregate consumption; Q: quality stock of capital goods.

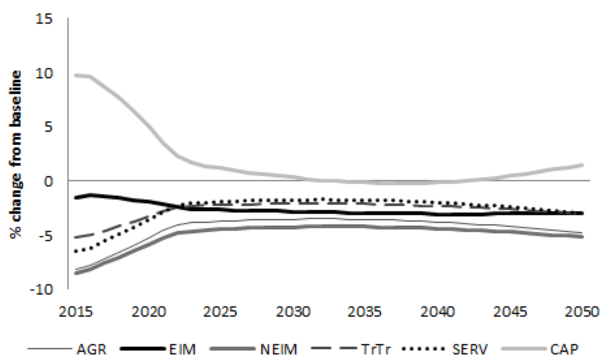

Figure 12: Impact of an energy tax on sectoral output

by a substantial welfare loss (Table 2). The generalized decline in process innovation in consumption good sectors (Figure 14) contributes to deteriorate energy productivity over time.

6 Conclusions

We present a new dynamic multisector CGE model that distinguishes between product and process innovation and separates innovation from technology adoption decisions, by including capital vintage in the style of the ISTC literature. The model better accounts for the complex network of technology flows we observe in the data. Important for the assessment of environmental policies, we represent technological change in investment goods not only as capital-saving but also as energy-saving.

Our findings indicate that it might exist a trade-off between environmental and innovation goals. In line with previous studies, our results show that a policy raising energy costs has a

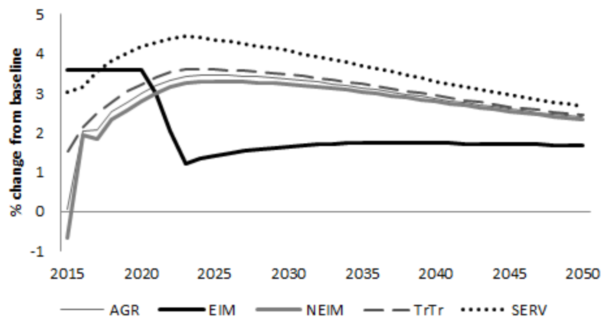

Figure 13: Impact of an energy tax on energy efficiency of the stock of durable goods

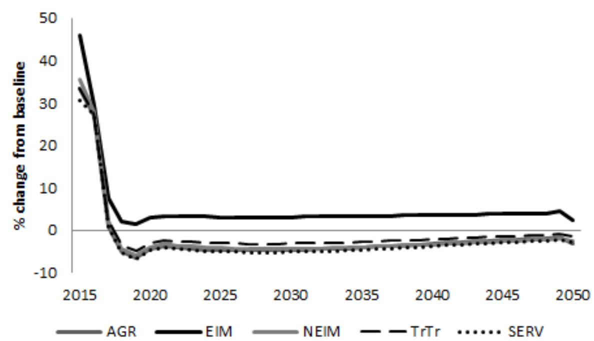

Figure 14: Impact of an investment subsidy on process innovation

detrimental impact on process-related R&D spending. However, the model is able to capture the response of product innovation in the capital good sector, which is instead positively affected by the tax.

Our analysis indicate that the endogenous investment in quality of durable goods is in fact crucial for economic growth and environmental goals. Hysteresis in the accumulation of physical capital, typical of models with capital vintages, calls for a careful consideration of a policy's impact on this type of product innovation even in the short run. The results of this paper are in line with the finding of the literature on ISTC, which highlights the importance of capital-embodied technology to drive productivity and sustain economic growth.

This paper presents interesting results in qualitative terms, but further robustness analysis is necessary to support our findings. More realistic policy exercises are planned, for instance the explicit modelling of pollution and an emission trading scheme, like the EU-ETS, that would allow to have more precise and comprehensive results on climate policy. Energy efficiency standards could also be analysed with our model. A very interesting extension is the analysis of alternative rebating schemes for the energy tax. The negative impact of the tax on innovation might well change if the revenues are used to cut input costs, i.e. labour. We leave for future research the accounting of human capital in the innovation

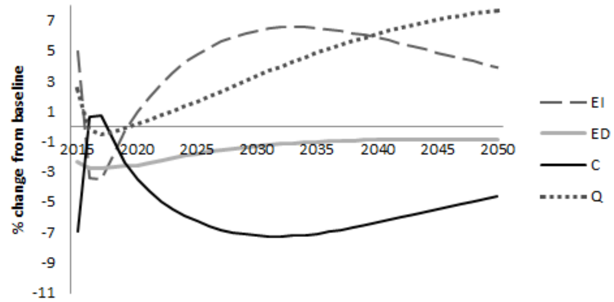

Figure 15: Macroeconomic impact of an investment subsidy

Note: EI: energy intensity; ED: energy demand; C: aggregate consumption; Q: quality stock of capital goods.

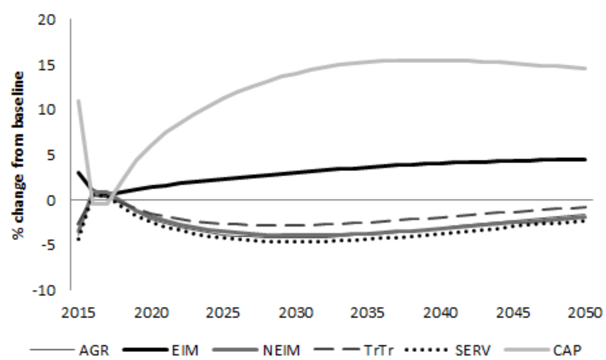

Figure 16: Impact of an investment subsidy on sectoral output

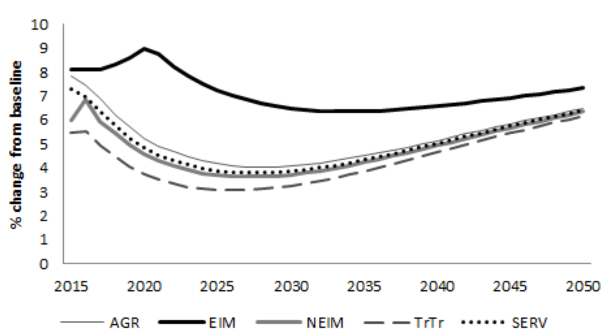

Figure 17: Impact of an investment subsidy on energy efficiency of the stock of durable goods

process and frictions in the labour market.

Finally, our study neglects knowledge spillovers. Several studies have already shown the welfare enhancing effect of R&D subsidies and we have a rather distinct focus. We are interested in the distinction between product and process innovation and we have no a priori information on the difference in the level of knowledge externalities between the two types of innovation. Apart from rent spillovers possibly related to product innovation (interesting for future research), the introduction of classic knowledge externalities would not enrich the analysis.

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Project Information

Welfare, Wealth and Work for Europe

A European research consortium is working on the analytical foundations for a socio-ecological transition

Abstract

Europe needs change. The financial crisis has exposed long-neglected deficiencies in the present growth path, most visibly in the areas of unemployment and public debt. At the same time, Europe has to cope with new challenges, ranging from globalisation and demographic shifts to new technologies and ecological challenges. Under the title of Welfare, Wealth and Work for Europe – WWWforEurope – a European research consortium is laying the analytical foundation for a new development strategy that will enable a socio-ecological transition to high levels of employment, social inclusion, gender equity and environmental sustainability. The four-year research project within the 7th Framework Programme funded by the European Commission was launched in April 2012. The consortium brings together researchers from 34 scientific institutions in 12 European countries and is coordinated by the Austrian Institute of Economic Research (WIFO). The project coordinator is Karl Aiginger, director of WIFO.

For details on WWWforEurope see: www.foreurope.eu

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