Endogenous Technical Change and Climate Policy: Effects of Research and Development and a Stock of Knowledge in a General Equilibrium Framework[*]

Ramiro Parrado

Fondazione Eni Enrico Mattei (FEEM)
Centro Euro Mediterraneo per i Cambiamenti Climatici (CMCC)
Ca' Foscari University of Venice

Andreas Löschel and Sebastian Voigt

Zentrum für Europäische Wirtschaftsforschung GmbH – ZEW

Abstract

The availability of reliable R&D data and the complexity of including it on a Social Accounting Matrix have proven a challenge to provide a multi-region and multi-sector database with R&D stocks and flows. This paper builds upon recent efforts to supply more consistent data on R&D and includes an Endogenous Technical Change specification in a global CGE model based on sector specific knowledge stocks. This allows analyzing the different implications of climate policies. An ETC model shows more flexibility for regions accumulating more knowledge. Investments in R&D and knowledge allow reducing a carbon tax burden in the future.

KEYWORDS: Endogenous Technical Change, Climate Policy, Research and Development, CGE Models.

JEL CODES: C68, E27, O1, Q54, O3

Address for correspondence:
Ramiro Parrado,
Fondazione Eni Enrico Mattei
Isola di San Giorgio Maggiore
30124 Venice, Italy.
Phone : 00 39 041 2700 451
Fax : 00 39 041 2700 412
Email: ramiro.parrado@feeem.it

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[*] This paper benefited from a fruitful collaboration with Andreas Löschel and Sebastian Voigt during a visiting period at the Centre for European Economic Research (Zentrum für Europäische Wirtschaftsforschung GmbH - ZEW) in Mannheim. I am also grateful to Francesco Bosello, Carlo Carraro, Enrica De Cian and Vincent Otto for helpful comments and discussions.
This paper is part of the research of the Climate Change and Sustainable Development Programme of the Fondazione Eni Enrico Mattei.

1 Introduction

The creation and accumulation of knowledge constitutes without any doubt one of the major drivers of progress and development. The incontrovertible evidence of that creative process is present everywhere in our daily routines and societies. However, it is rather difficult to define a measure of knowledge and then link it to economic development. Albeit the paradoxical fact that the empirical estimations of economic growth are based on a residual defined by Solow as the “measure of our ignorance”, the efforts to provide new methods and theories to explain economic development have produced many concepts and methodologies. One of them is the endogenous growth based on research and development (R&D) that contributes to build a stock of knowledge. Hence, there has been a growing concern to include those activities as part of national accounting. Within this context, many countries have started to produce R&D satellite accounts following defined rules and linking the Frascati manual (OECD, 2002) to the System of National Accounts. These efforts imply that detailed work has been carried out at the sectoral level within national accounts to identify and classify R&D expenditures following those linking guidelines.

The data structured in the system of national accounts provides the basis for extensive analysis by allowing the construction of input-output databases and also social accounting matrices in which computable general equilibrium (CGE) models are based on. CGE models are a useful tool for policy analysis. They are also used in climate change assessments considering both potentially wide economic impacts of inaction as well as possible responses through different climate policy alternatives. In this context, the provision of R&D data constitutes a fundamental step to consider the implementation of endogenous technical change (ETC) in different modelling exercises. Moreover, considering explicitly ETC establishes a crucial issue in policy and impact assessments since the inclusion of feedback mechanisms allows a better understanding of direct and indirect effects.

Most of the general equilibrium framework literature with a focus on modelling R&D induced technical change is based on aggregated growth models (e.g. Smulders and de Nooij, 2003) or optimal growth models considering macro regions (e.g. Nordhaus, 2002; Buonanno et al. 2003, Popp, 2004, Carraro and Galeotti, 2004; and Bosetti et al. 2006a). There are fewer studies using multi-sector CGE models taking into account knowledge stocks at the national level. For instance, while Goulder & Schneider (1999) estimate a stock of knowledge related to four aggregate industries of the US economy for 1995; Sue Wing (2003) and Otto et al. (2008) refine that approach by including knowledge stocks in a social accounting matrix (SAM) framework. Until now, the availability of reliable R&D data and the complexity of including it on a SAM have proven a challenge to provide a multi-region and multi-sector database with R&D stocks and flows.

This paper builds upon the recent efforts to supply more consistent data on R&D and the previous experiences to model technical change. It adds to the literature by introducing an ETC specification in a global CGE model based on sector specific knowledge stocks. This allows analysing the different implications of selected policies, including trade, R&D, and technology transfers. Accordingly, the main contributions of this paper are: i) to produce a coherent and integrated database including region and sector specific flows and stocks of knowledge, based on a SAM structure, ii) to extend a multi-sector and multi country CGE model with a knowledge-based endogenous technical change specification using the integrated database, and iii) to use the improved model for assessing the differences and implications of a carbon tax policy over a traditional autonomous (exogenous) technical change formulation.

The modified CGE model shows more flexibility for regions than can accumulate more knowledge. Investments in R&D and knowledge stocks allow reducing a carbon tax burden in the future. The model with ETC produces a slightly higher cost of climate policies in terms of gross world product, but at the same time a lower world carbon intensity. Moreover, in the presence of a carbon tax, there are redistributive effects on R&D investments and knowledge accumulation. High carbon based fuels reduce their output while other industries increase their production. However, during the first years of the implementation of the carbon tax, there is evidence of a market size effect that increases R&D investments in sectors with a significant size such as the coal industry. When a carbon tax is imposed, the accumulation of knowledge is lower either when the capital-energy substitution is higher, or when elasticities of supply for fossil fuels are lower.

The remainder of the paper is organised as follows. The next section contains a brief description of the literature regarding ETC. Section 3 describes the modification of the GTAP database to include the stock of knowledge and R&D services. Section 4 introduces the modelling of R&D services and the accumulation of a stock of knowledge and provides a description of the model used for its implementation. Section 5 illustrates the results of a simple policy experiment with the objective of isolating the net effect of ETC. Finally, section 6 concludes.

2 Endogenous technical change in a modelling framework

The role of technology has become more preponderant in a context where concerns related to climate change and growth are among the priorities of a sustainable development agenda. Although technology is a key element in explaining growth as well as one of the proposed instruments to deal with climate change, it may also be influenced by climate policy. In a recent survey about the influence of environmental policy on technical change and innovation, Carraro et al. (2010), review the literature and divide it in two groups: an ex-post analysis mostly based on econometric studies and an ex-ante analysis with contributions that come from integrated assessment models. Different kinds of environmental, economic, and energy models for the analysis of mitigation policies have been gradually evolving from considering technological change as an exogenous element to include it as an endogenous mechanism, in accordance with theories such as endogenous growth, innovation, and learning-by-doing.

In the existent literature, some common elements can be identified as the most important and interconnected concepts related to ETC: i) a stock of knowledge and human capital that drives growth, ii) investment in R&D, iii) technology learning, iv) technology diffusion, and v) technology spillovers (Romer, 1990; Weyant and Olavson, 1999; Löschel, 2002; Keller, 2004; Gillingham et al., 2008; Pizer and Popp, 2007).

Knowledge and technology are the outcome of investment in research, development and learning; both are considered as non-rival and partially excludable goods (Romer, 1990, Keller, 2004). Whereas non-rivalry allows for knowledge accumulation, the diffusion of that type of good can only be partially controlled by the producer depending on technological and legal aspects. These features open the possibility for additional productivity improvements offered by spillovers that benefit others, besides the producer of knowledge or technology. Notwithstanding these potential benefits, in spite of the knowledge availability, an adequate absorptive capacity is necessary to understand and use that knowledge or technology (Grubb et al., 2006).

Regarding the inclusion of ETC in a modelling framework, it is necessary to consider the modelling approach and the corresponding endogenous specification. Originally, there were two general types of modelling methodologies. The first is the bottom-up approach, which contemplates more detail in technologies and is based on engineering concepts implemented in partial equilibrium or energy system models. The second type is the top-down approach based on economic concepts. It usually has a higher degree of aggregation. For instance, computable general equilibrium (CGE) and macroeconometric models belong to the top-down approach. The efforts to bridge the gap between top-down and bottom-up models raised a hybrid approach, which intends to take advantage of the strengths of both categories. It increases the formalisation of some sectors while also paying attention to macroeconomic issues. Böhringer and Rutherford (2008) distinguish three sub-categories of the hybrid approach: i) linking existing model types, ii) including the core of one model in a reduced form within the other type of model, and iii) completely integrating both kinds of models by using mixed complementary techniques for their solution. Furthermore, within each approach and when considering the specifications for ETC, the main focus could be broadly classified either on R&D and the accumulation of a knowledge stock, or on learning curves based on one or two factors (Grubb et al., 2006, Pizer and Popp, 2007).

In the top-down approach, more aggregate and optimal growth models follow a more integrated method not only considering economic models, but also energy systems, natural resources and climate. These models contemplate an optimisation path, which offers a normative view regarding the future behaviour of key variables. Their ETC specifications are based on an aggregated stock of knowledge, some of them focusing on energy and non-energy industries or in environmental and non-environmental R&D (Buonanno et al., 2000; Nordhaus, 2002; Buonanno et al., 2003; Carraro and Galeotti, 2004; Popp, 2004; Bosetti et al., 2006a). As for the hybrid approach, normative insights are enhanced with the inclusion of a detailed energy system description that also takes into account investments in R&D and learning-by-doing (Bosetti et al., 2006b; Bosetti et al., 2007; Carraro et al., 2009).

Multi-sector CGE models offer a more complete description of an economy with a more detailed sectoral and regional breakdown. While CGE models may lack a comprehensive energy description system, they offer more exhaustive information on intersectoral and international flows. This creates a potential advantage for endogenous technical progress derived from technology, knowledge, and trade spillovers since they can include not only energy R&D but also R&D for the rest of the sectors in the model (Goulder and Schneider, 1999; Sue Wing, 2003; Kemfert, 2005; Otto et al. 2007, Otto et al. 2008, Otto and Löschel, 2009). There is also a recent study considering gains from specialisation that drive endogenous growth based on an intermediate good composite (Schwark 2010).

Although the selection of the approach specification is not exclusive, it depends on the detailed formalisation of the model and the available information either for R&D data or for specific learning curves. Typically bottom-up models have focused on learning curves while the more aggregate models under the top-down classification have followed an R&D specification. Among those top-down models that use R&D, there is also a distinction of R&D devoted to energy production and to other intermediate goods. This distinction is useful to account for specific technological progress in sectors that should pollute less, such as energy producing industries and the rest of the economy. An adequate combination of the modelling approach and ETC specification depends on the features of the model, its flexibility, and the information that should be included. For instance, given the detail of energy sectors in bottom-up models, a learning curve is more likely to be included for each sector as long as there are studies with that information. In the case of top-down models, where there are not enough details about an industry, it is preferred to select the alternative specification of R&D with a stock of knowledge.

Since CGE models offer the possibility to work with a broader sectoral and regional detail, it is possible to take into account the channels through which knowledge and technology spillovers mainly operate: trade, labour mobility, and R&D. A reasonable alternative is to include a stock of knowledge, which is the product of investment in R&D activities (Gillingham et al., 2008, and Pizer and Popp, 2007). Some models include knowledge capital in their production functions as reported by Gillingham et al. (2008), which is also related to R&D expenditures. Alternative examples are Goulder and Schneider (1999), Sue Wing (2003) and Otto et al. (2007).

3 Introducing Research and Development and a stock of knowledge in the GTAP database

According to the literature, including a knowledge capital stock product of investments in R&D allows to provide an endogenous growth source along physical capital accumulation.

Although there are some challenges regarding the integration of additional data related to R&D and the stock of knowledge, the corresponding benefit is the possibility to provide details about the interaction between sectors including spillovers from trade or R&D.

Different data sources have been considered to include R&D activities and the related stock of knowledge in the Global Trade Assistance and Production (GTAP 7) database. Gross Expenditures on Research and Development from UNESCO and the World Development Indicators are the starting point and reference for countries' expenditures on R&D. The sectoral breakdown has been obtained by using the ANBERD database as the main reference which presents detailed information on business enterprise R&D by industries for OECD countries. Combining all those data sources, we produced an extended dataset modifying the GTAP database to include a stock of knowledge for every region with the corresponding R&D services in the form of a new endowment used by all sectors. The stock of knowledge has been computed following the perpetual inventory method according to a reclassification of the R&D expenditures. These were initially taken into account as intermediate consumption in the original database; now they are considered as investments in R&D through the use of the additional primary factor. An implication of this reclassification is that GDP is increased according to the use of the new R&D endowment following the existing considerations of the literature.

The sectoral breakdown for R&D expenditure is available for approximately 38 OECD countries from the ANBERD database with high detail for manufacturing industries. There is a remaining aggregate value for the rest of the sectors in the economy and these data were distributed for non-manufacturing sectors taking into account its value added share of each country's sector according to the GTAP 7 database.[1] In addition and given that there is no information about most energy sectors, energy R&D data has been complemented using the IEA's R&D budget (IEA, 2010) which mainly refers to public expenditure. Nevertheless, it could be taken as a reasonable proxy in order to estimate the final shares of R&D for every sector in the economy.[2]

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[1] Almost all remaining sectors in the GTAP database have been considered with the exception of two sectors: ROS (Recreational and Other Services) and DWE (Dwellings) for which R&D was set to 0.

[2] The correspondence between sectors in the GTAP and the ANBERD datasets has been elaborated following the ISIC Revision 3.1 (United Nations, 2002).

For the rest of the countries where there was no detailed data for R&D expenditures by industries there were two alternatives. A direct method could use the value added shares to distribute the R&D expenditure while a more fit method would use the shares from the ANBERD dataset to extend those shares to the rest of the world. For this purpose, the countries from the ANBERD dataset with the detailed sectoral breakdown were divided into three groups according to the average production share in different aggregate sectors. This was done in order to find similar groups in terms of the industrial structure with respect to their share of production in the primary, secondary, and tertiary sectors. We exploited the GTAP 7 database for this step due to consistency reasons. Moreover, the main criteria used for the classification were the shares of the services and manufacturing sectors. Following this, we used the same classification for the rest of the GTAP regions. Finally, the average R&D expenditure sectoral structure of each ANBERD group was imputed as a proxy for the rest of the countries in the GTAP database according to the group they belonged to.

A reclassification of R&D expenditures as knowledge capital formation in the GTAP database is not a straightforward task given that some considerations must be made prior to this task. First, including a stock of knowledge in the GTAP database implies creating a new endowment representing flows to households as remunerations for the use of knowledge. This means that those flows are, as in every endowment, registered as domestic within the country and disregarding its ownership. Second, although there are some concerns about identifying international R&D flows as imports and exports (De Haan et al., 2007); the information from the selected sources does not provide these trade flows. Moreover, and taking into account the presence of international R&D spillovers (Coe and Helpman, 1995), it seems an adequate choice to reclassify the expenditures from the original sector which are only domestic, without making any assumption about R&D exports or imports. Third, all modifications should be done in such a way that the database remains balanced. The final outcome of this process is a set of global satellite R&D expenditures constructed and adapted according to the data of the sector in which R&D was originally classified. With these values it is possible to compute the corresponding flows for investment on a steady state following the formula proposed by Paltsev (2004):

$$INV\_R\&D_{i,r} = \frac{(\delta + g_{i,r})}{\delta + r_r} \cdot R\&D\_services_{i,r}$$

where ***$INV\_R\&D_{i,r}$*** is the investment in R&D for every sector within every region and the last term, ***$R\&D\_services_{i,r}$***, is the value that was reclassified from the intermediate consumption to payments for R&D services. The remaining parameters are of crucial importance in computing both knowledge stock and its investments: ***δ*** is the depreciation rate set to 20%,[3] ***$g_{i,r}$*** is the growth rate computed as the average growth of each GTAP sector output from 1997 to 2004,[4] and ***r_r*** is the net rate of return to R&D. Estimations of the private rate of return on R&D provide values that are higher than those of the return on physical capital.[5] In this study we use the rate of return from every region in the database for 2004 as reference for physical capital. It is computed as the net return of the capital endowment earnings divided by the regional capital stock. In order to have the gross rate of return, the depreciation is added. We then compute the corresponding gross rate of return to R&D by multiplying that value by four. Finally we calculate the net rate of return to R&D by deducting its depreciation rate.

Regarding the stock of knowledge, the formula to compute the capital stock in the steady state according to the Solow model is (Caselli, 2005):

$$Know\_Stock_{i,r} = \frac{INV\_R\&D_{i,r}}{\delta + g_{i,r}}$$

where ***$Know\_Stock_{i,r}$*** is the sector specific stock of knowledge within every region taking into account the R&D expenditures or payments for its use. Using this value, it is also possible to compute the corresponding depreciation of the knowledge stock for the database.

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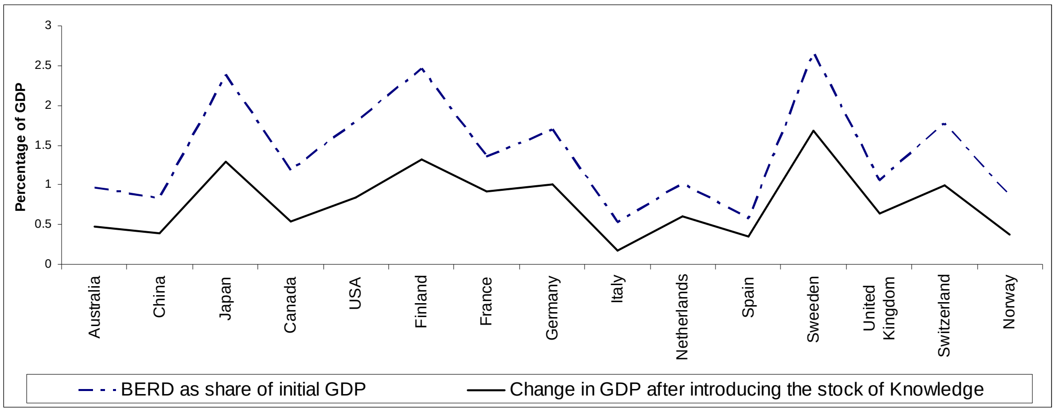
[3] The depreciation rate is in the range of different empirical estimations using different methods. Berstein and Mamuneas (2006) estimate R&D depreciation rates for the following US R&D intensive industries: chemical products (18%), non-electrical machinery (26%), electrical products (29%) and transportation equipment (21%). Mead (2007) also provides a literature review for seven studies in the US with depreciation rates within a range from 12% to 29% for all R&D capital and within 1% to 52% for industry-level R&D capital.

[4] Although the range for the computed growth rates for every sector was between -86% and 440%, for the estimation of the knowledge stock the minimum growth rate was set at 0.5% while the maximum was set to 20%.

[5] An extensive review of econometric estimations for the returns to R&D for the last 50 years is available in Hall et al. (2010), who find a likely range for private returns between 20% and 30% but with values as high as 75% or more, using a production function estimation approach; and between 10% and 20% taking into account estimates from a cost or profit function. These values are clearly much higher that the gross physical capital rate of return implicit in the GTAP database, which is around 11% for the world average. Regarding a comparison between rates, Bernstein (1989) provides a relationship between gross rates of return both for physical capital and R&D capital and finds that the rates of return of R&D capital are between 2.5 to 4 times greater than those of physical capital.

The outcome at this point is a new database that includes the stock of knowledge and its related flows. As a consequence of including a new type of endowment and the stock of knowledge, the database now produces a slightly higher GDP because of the new investments and services related to R&D.

Figure 1: Effects on GDP of capitalizing Business Expenditures R&D



The effects of capitalising R&D expenditures on GDP depend on the type of sector of performance and are described in detail by Fraumeni & Okubo (2005).[6] Figure 1 displays the effect on GDP of capitalising business expenditures R&D for selected countries. The figure also shows the initial BERD data as a share of GDP, which is not so far from the new R&D shares computed after the adaptation of the satellite R&D data to the GTAP database.

After including the stock of knowledge, there are two new flows in the database that are worth comparing to the initial BERD data. Figure 2 shows that the R&D investments and remunerations are close to the initial data, in particular for OECD countries from the ANBERD database. It is also worth mentioning that the differences between R&D compensations and investments within every country arise due to the fact that these are national aggregate figures and because every sector has different R&D expenditures. Their capitalisation was computed taking into account their own growth rates.

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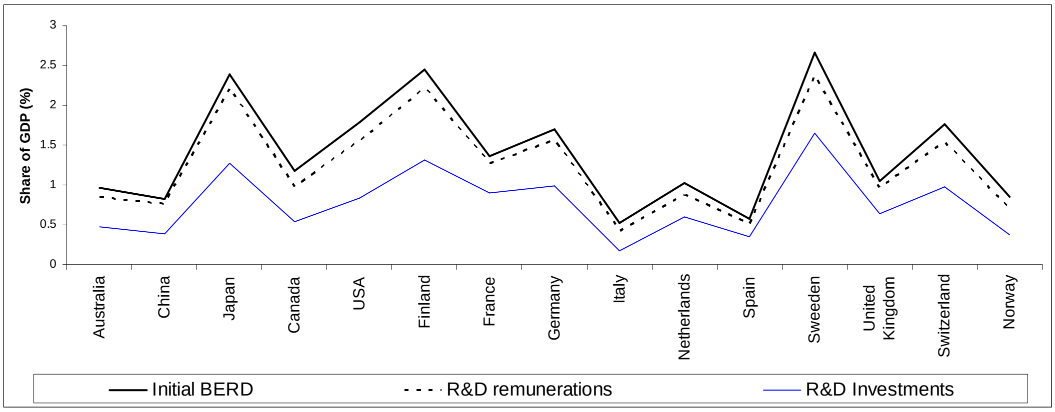
[6] See Fraumeni & Okubo (2005) p. 283.

Figure 2: R&D expenditures in the new database



4 Modelling R&D and the stock of knowledge

The addition of a stock of knowledge as a new production factor unlocks further sources for endogenous growth not only due to its accumulation, but also because it opens the possibility to consider externalities related to R&D services. For the ETC specification we mainly refer to Goulder & Schneider (1999) and Otto et al. (2008). Consequently, the final output in sector i (Y_i) is produced by combining the stock of knowledge (H_i) with a composite X_i, which is the output obtained by combining production factors (physical capital K, labour Lb and land Ln), energy commodities E and other intermediate inputs M. The parameter ρ is related to the elasticity of substitution between the knowledge stock and the composite X_i, σ: $\rho = (\sigma\text{-}1)/\sigma$, and its value has been set to 1, as in Goulder & Schneider (1999) and Otto et al. (2008).

$$Y_i = \overline{H}_i \cdot \left[\alpha_i \cdot H_i^{\rho} + (1-\alpha_i)\cdot X_i^{\rho}\right]^{\frac{1}{\rho}} \tag{1}$$

$$X_i = f\left(K, Lb, Ln, E, M\right) \tag{2}$$

$$\overline{H}_i = H_i^{\gamma_i} \tag{3}$$

Furthermore, $\overline{H}_i$ is a total factor productivity index representing technological progress, which drives productivity growth in sector i. In fact, the increase in the technology index $\overline{H}_i$ represents intra-sectoral spillovers from sector specific knowledge capital (Goulder and Schneider, 1999). Firms directly benefit from R&D investments in their own stock of knowledge H_i since it is excludable. In addition, they also benefit indirectly through $\overline{H}_i$ being non-excludable knowledge. The indirect effect is regulated by parameter $\gamma_i>0$, which might be interpreted as the elasticity of R&D services to total factor productivity in every industry.

The value for this elasticity is set to 0.09, based on the empirical estimations from Coe and Helpman (1995).[7] Knowledge stocks accumulate with new investments in the form of R&D expenditures, $R_{i,t}$, less the corresponding depreciation of the existing stock ($\delta^H = 0.2$).

$$H_{i,t+1} = \left(1 - \delta^H\right) \cdot H_{i,t} + R_{i,t} \qquad (3)$$

Investments flows are allocated in three stages. First, total investments are allocated to every region by a global bank. Second, after the total amount is determined for every region, investments in R&D and physical capital are distributed according the corresponding rates of return in order to equalise them in the long-term. In the last stage, the R&D investments are allocated among all sectors within a region taking into account their own rate of return and the fact that knowledge capital is sector specific and treated as a sluggish endowment.

This specification was introduced in a CGE model to evaluate the differences with a formulation following an autonomous technical change, which is set exogenously. This study relies on a recursive-dynamic CGE model of the world economy, ICES (Intertemporal Computable Equilibrium System), in which different regions interact with each other through several channels: prices, capital, and trade flows. ICES is based on the GTAP-E model (Burniaux & Truong, 2002), and uses the GTAP 7 database with the additional information regarding the stock of knowledge and R&D services. A figure of the enhanced model’s nested production tree is in Annex 2, along with a summary of its substitution elasticity values and the detail outlining both regional and sectoral aggregations.

5 Simulation results

This section presents the results of the extended model and database. For this purpose, we first set out a baseline scenario as reference for a policy simulation based on a carbon tax. After a brief description of the baseline scenario, we first consider the general impacts of the carbon tax on GDP and CO_2 emissions in the model with no ETC. Afterwards, we focus on

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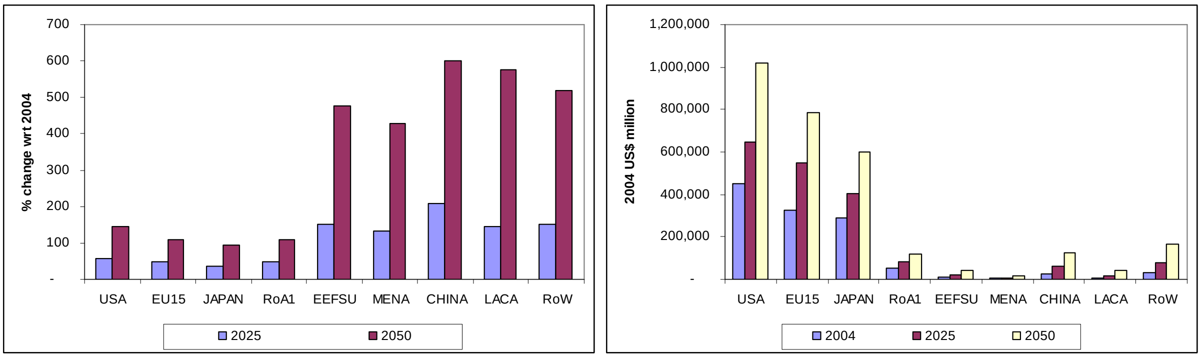
[7] The existence of sector specific knowledge stocks opens the possibility to model intersectoral and also international spillovers considering the sum of the knowledge stocks from the remaining sectors and regions as in Buonanno et al. (2003), or also considering the concept of absorption capacity as in Bosetti et al. (2008). These are further model developments, which should consider either an adequate set of parameters for the intrasectoral spillovers for the first case or a definition of absorptive capacity coherent with the new database for the second case.

the net effects of explicitly considering ETC on the following variables: GDP, CO_2 emissions, energy demand, sectoral outputs and knowledge accumulation.

5.1 Evaluating the effects of introducing ETC in CGE modelling

For the analysis of the differences of both modelling alternatives we calibrated two identical baselines, which constitute the common ground to compare the effects of both specifications, by simulating the same policy in order to identify the main differences. For this purpose, we first produced a baseline with the ETC specification as described above for the period 2005-2050 and then a second baseline with autonomous technical change that replicates the regional GDP and sectoral output of the ETC baseline in every region. This was done by exogenously calibrating the autonomous technical change (total factor productivity) parameters in such a way that the mentioned outputs show the same trend and behaviour, but remain constant without reacting to endogenous price changes that could also be triggered by specific policies. Within this framework it is possible to disentangle the contribution and importance of an ETC formulation over the traditional autonomous technical change specification, in particular when a certain climate policy is implemented.

Figure 3: Baseline GDP growth assumptions and knowledge stock accumulation



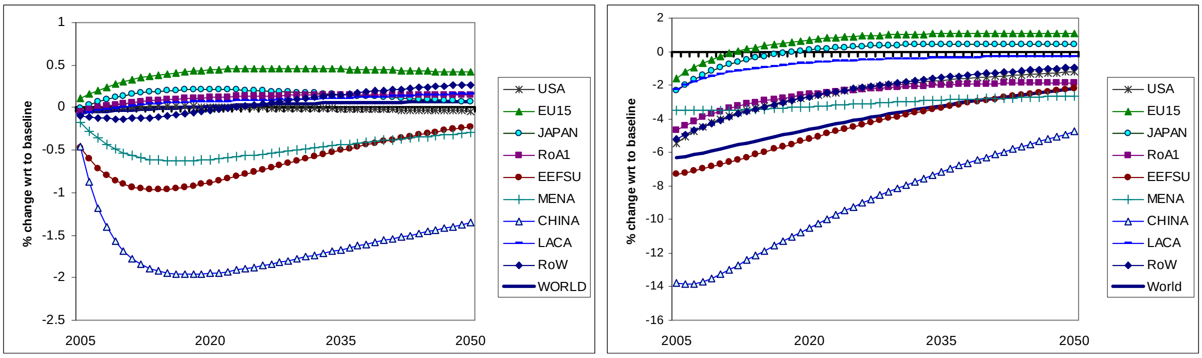
a) Real GDP growth ***b) Knowledge stocks***

The baseline's GDP growth assumptions are shown on the left panel of figure 3. Developed regions grow at a much lower rate than developing countries reflecting some convergence given that the latter show faster growth rates. In addition it is also possible to identify a group of developing regions growing at a more accelerated pace (China, Latin America and the Caribbean -LACA-, and the Rest of the World -RoW). While these growth rates are common for both baselines, the main difference is the knowledge stock that cumulates through time in the ETC specification as shown at the right panel of figure 3. As expected, developed regions account for a considerable knowledge stock while developing regions have a much smaller amount but accumulate more according to their development.

5.2 *The contribution of endogenous technical change in climate policy evaluation: A simple experiment*

To test the initial implications of considering a stock of knowledge in the endogenous growth model, we imposed a uniform carbon tax[8] of 25 and 50 US$ per ton of carbon[9] throughout the period 2005-2050. To isolate the effect of the ETC addition, we first computed the effect of the carbon tax on GDP, CO_2 emissions and sectoral output for both the ETC and No-ETC specifications and then calculated the net difference. All figures are expressed as percentage changes with respect to the baseline value. Figure 4 shows the final net effects on GDP (left panel) and CO_2 emissions (right panel) of the carbon tax in the original model without ETC after the 50 US$ carbon tax has been imposed.

Figure 4: Impact of a carbon tax on regional GDP and CO2 emissions: No ETC model Difference with respect to baseline 2005-2050. (in percentage)



a) Real GDP ***b) CO_2 emissions***

Imposing a uniform carbon tax, from 2005 to 2050, produces two different effects on GDP and CO_2 emissions. In principle, it has a recessionary effect reducing output and emissions in all regions. However, the effect on GDP in the left panel shows developed countries with a slightly higher GDP (e.g. less than 0.5% for EU15) and developing ones with considerable reductions (e.g. more than 2.5% reduction for China). This outcome is mainly due to international trade. Although the majority of exports decline, there is an increase of exports

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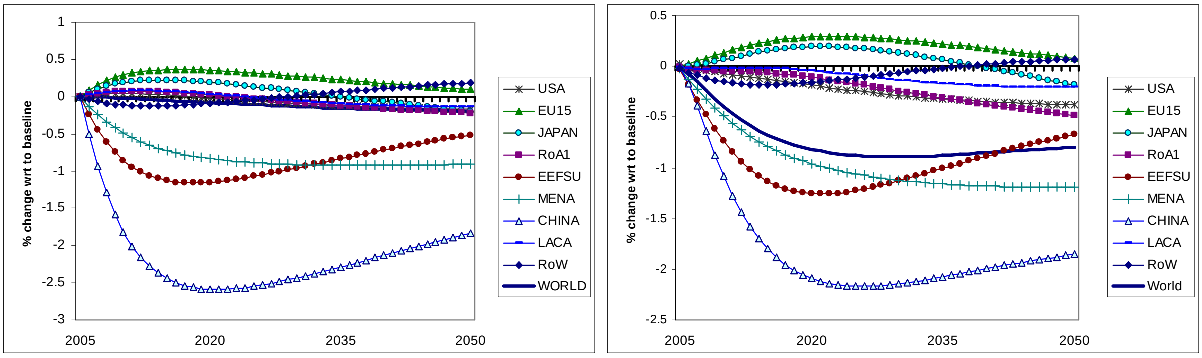
[8] The climate policy in ICES is simulated by introducing a tax on CO_2 emissions related to the use of fossil fuels. It is basically modelled as a tax levied on the carbon content of each fuel (coal, oil, gas and oil products), which is released to the atmosphere through combustion during an economic activity.

[9] The first value was set as in Goulder & Schneider (1999) to compare their qualitative findings. They are equivalent approximately to 7 US$ and 14 US$ per ton of CO_2 respectively. Regarding our simulation results for both carbon prices, results are qualitatively similar with the only difference that effects with 50 US$ per ton of carbon more than double those from 25 US$ tax.

from energy intensive industries, particularly in developed regions. In addition, export prices of those industries increase with respect to the baseline case.[10] In contrast with GDP, CO_2 emissions reduce everywhere at the beginning although reductions are lower at the end of the period. The decline of emissions in the right panel is more evident in developing countries mainly due to the fact that those economies have a higher carbon intensity of GDP. After looking at the carbon tax impacts on the model with no ETC, the following figures will illustrate the net effect of an ETC specification compared to a model without ETC.

Figure 5 presents the net effect of ETC considering the same carbon price of 50 US$ per ton of carbon. The ETC specification enhances the final effects on real GDP of introducing the carbon tax (Figure 5, left panel). The highest positive impact is on Europe (EU15) GDP with an additional increase of 0.36%, while the highest negative impact is on China’s GDP with a decrease of -2.59%. World gross product is lowered by -0.19%. The expected effect of an ETC specification is an expansion of output in all regions, but the interaction with the carbon tax produces a compounded effect where the influence of the tax prevails.

Figure 5: Impact of a carbon tax on regional GDP and CO_2 emissions:
Net effect of ETC with respect to baseline 2005-2050. (in percentage)



a) Real GDP ***b) CO_2 emissions***

Developed regions that slightly increase their GDP have a positive feedback on output (EU15, Japan, and RoA1 in the left panel) as well as on emissions (EU15 and Japan in the right panel). The initial positive effect allows developed countries to accumulate more investments in physical capital as well as knowledge reinforcing their positive feedback. Symmetrically, developing regions that have a higher burden because of the carbon tax cannot increase their physical and knowledge capital as in the baseline case. In fact, that burden considerably

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[10] The impact of a carbon tax on aggregate exports and prices for the model without ETC in shown on tables A1 to A4 on the annex, by sector and region for 2010 and 2050.

lessens R&D investments and therefore enhances the initial loss of GDP especially at the beginning of the period.

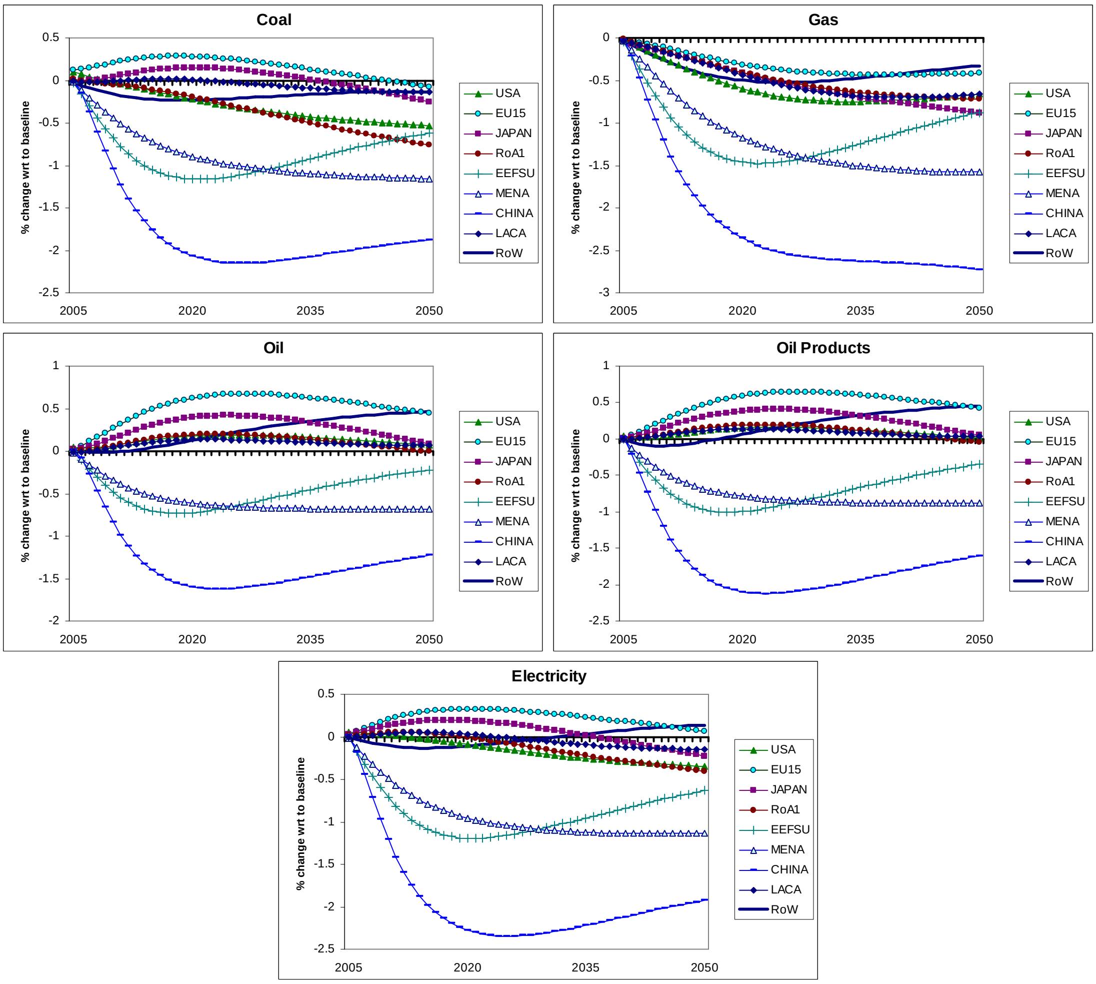
The group that has a net positive impact in the first twenty years consists mostly of developed countries and this outcome is explained because their initial knowledge endowments allow them to report gains from their relative positions after the carbon tax has been imposed. On the contrary, the group of countries which suffer an enhanced loss with the ETC specification have a relatively smaller stock of knowledge in the beginning of the period. This feature highlights the fact that a model with ETC is more elastic in the sense that it magnifies the initial differences. Moreover, those differences grow towards the middle of the period depending on the available knowledge. However, at the end of the considered time horizon the gap becomes smaller given that the developing regions have accumulated more knowledge as seen in the right panel of Figure 3.

In particular, this outcome can be observed for China, Eastern Europe and Former Soviet Union (EEFSU) and the Rest of the World (ROW) whereas Middle East and North Africa (MENA), which have lower knowledge stocks, do not notice a reduction of that breach before 2035. Nonetheless, the pace of the gap’s increase decelerates, suggesting that it will become smaller in the following years. Moreover, with ETC there is a slightly higher loss when considering the Gross World Product (GWP) represented as the blue thick line in the first panel of Figure 5.

The rational behind the increase of GDP for developed regions lies in the fact that the carbon tax increases the carbon-based energy prices and therefore production costs. However, the knowledge stock, which is also a production factor, is not directly affected by the carbon tax. Therefore, as long as a sector has a considerable knowledge stock it will be able to substitute the increasing cost inputs (carbon-based energies) with knowledge. The case for developing regions is that, as said before, their knowledge stocks are much lower reducing the possibility to substitute carbon-based energies. R&D investments over time play an important role in this case, since they build knowledge and therefore, increase the substitution possibilities. However, given that the carbon tax is recessionary in particular for developing regions, the growth rate of R&D investments is also affected, reducing the output growth rate from the beginning of the tax implementation.

The behaviour of CO_2 emissions at the regional level shows a similar trend to real GDP, especially in the first half of the period, corroborating the identification of two groups of regions (Figure 5 right panel). Developed regions increase their emissions mainly due to a substitution effect while developing countries reduce their overall emissions since their output experience a slowdown. It is also important to notice that the increased reduction begins to attenuate from 2020. There is also a slight increase of emissions from EU15 (0.30%) and Japan (0.20%) with a peak in 2020. This could be regarded as a rebound effect to the carbon tax, given an increase in energy use in some fuels. The final ETC effect is an overall reduction of world CO_2 emissions by -0.90%, and comparing this variation with that of GDP the ETC formulation shows lower carbon intensities given that emissions reduce more than GDP.

Figure 6: Impact of a carbon tax on energy demand by type of energy:
Net effect of ETC with respect to baseline 2005-2050. (in percentage)

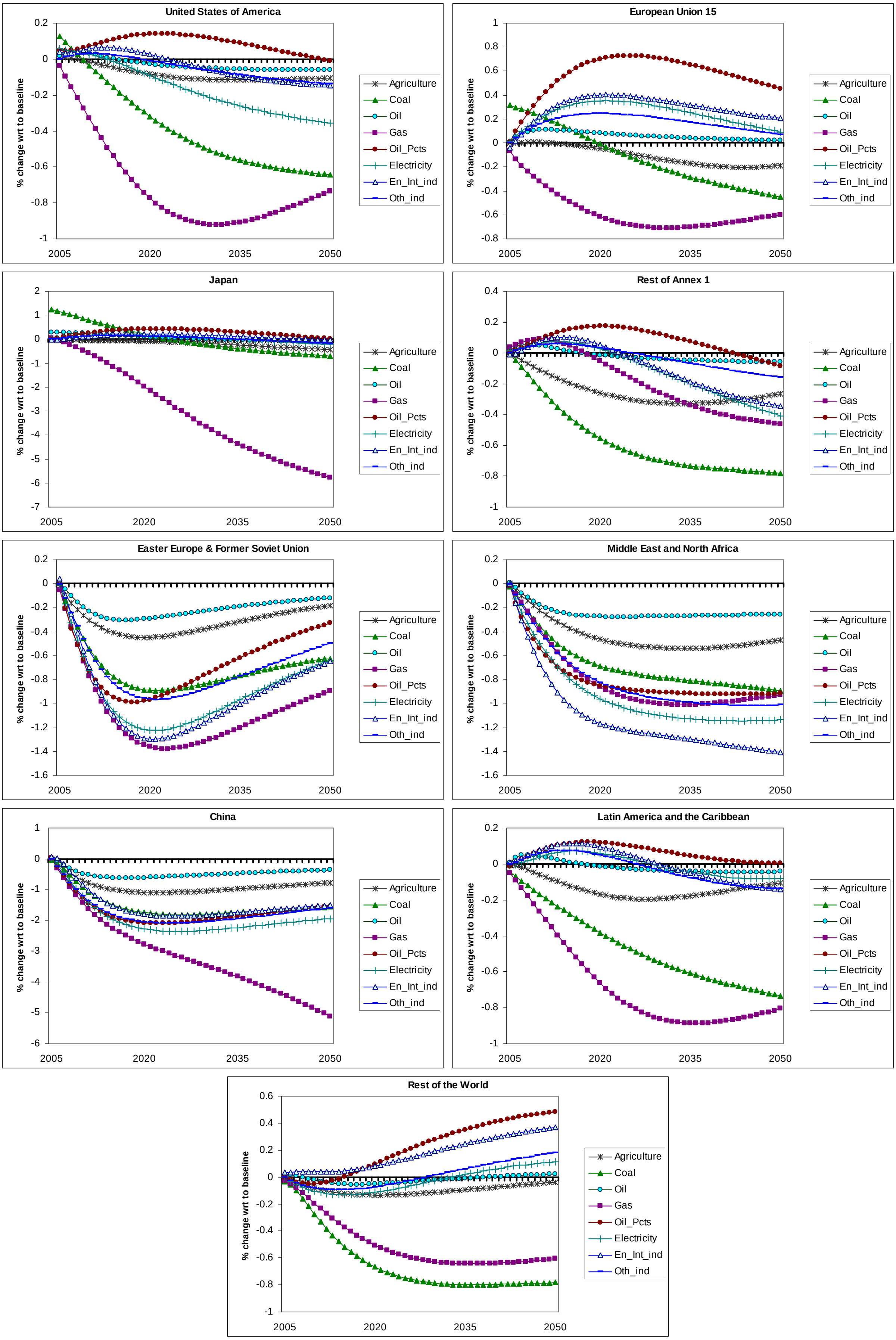


The net effect on emissions is explained by looking at variations in energy use due to the compounded influence of the carbon tax and the ETC specification. Figure 6 illustrates the final effect on the evolution of each type of energy demand for all regions. In fact, developed regions increase their energy demand for all types of energy but gas. The major part of this energy demand comes from both the electricity sector and the energy intensive industries in the beginning for coal, and afterwards for oil products.

Effects on GDP can be better understood by observing the variation in output of the different industries shown in Figure 7 as difference between the ETC and no-ETC specifications. In this context and before analysing them in detail it is worth mentioning the findings of Goulder and Schneider (1999) when they consider the effects on four macro industries. For conventional (carbon based) fuels, the reduction of output is higher in the presence of induced technical change, while for alternative fuels there is a positive effect that in certain periods becomes a gain instead of a loss. Finally they report a consistent loss in the remaining industries, (carbon intensive and non-carbon intensive), due to the fact that the tax burden effect dominates through a scale effect reducing their output.

Turning back to Figure 7, the detail of output by industry and region corroborates the groups identified with the effects on GDP, and provides further information. Developed regions show a redistribution of sectoral production due to the carbon tax highlighting a higher induced technical change on oil products, energy intensive industries as well as other industries and the electricity sector especially at the beginning of the period, while coal and gas production is reduced at the end of the period. For these particular regions and regarding the effects on sectoral output, our results confirm Goulder & Schneider's (1999) insights for the fossil fuels industry particularly for coal, gas, and oil whose use is reduced when ETC is active. A paradoxical outcome of the carbon price in developed regions constitutes the fact that there is an initial increase of coal during the first decades. This particular result is explained by a high elasticity of supply relative to other fossil fuels, allowing coal production to be more flexible. The remaining sectors show a positive effect when ETC is introduced, with the exception of agriculture. This is because its stock of knowledge is lower in relative terms.

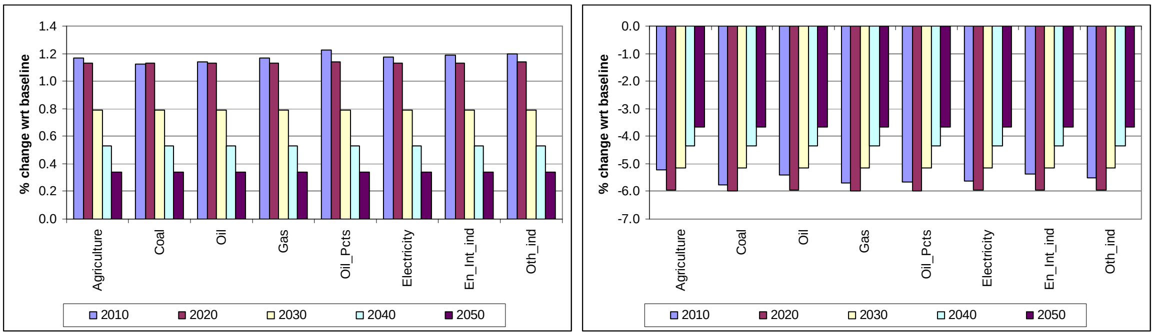
Figure 7: Carbon tax Impact on output: Net effect of ETC with respect to baseline (2005-2050)



In the case of the group of developing regions that reduce their GDP, the figures show the predomination of a scale effect with almost all industries suffering a contraction of their output. In these cases it is also possible to appreciate a substitution effect, but with the opposite outcome: industries that reduce their output less are intensive carbon based fuels with higher reductions for the rest of the sectors. Notwithstanding the diminishing effect of ETC, the gap that grows from the beginning starts to decline in the middle of the period. Furthermore, this is a sign of the flexibility of the ETC specification since the knowledge stock influences the results and also allows inverting the trend when knowledge increases in developing countries especially EEFSU, China and RoW. Latin America and the Caribbean show a trend similar to developed regions at the beginning of the period with higher outputs for electricity, energy intensive, oil products and other industries. However the trend inverts at the middle of the period as coal and gas constantly reduce throughout the period.

Finally, it is worth observing what happens with the knowledge accumulation after the carbon tax has been introduced. Figure 8 shows the impact of the carbon tax on knowledge accumulation for EU15 which has an increasing GDP (panel a), and China that faces a higher burden of the tax (panel b). For the case of EU15, the sectors that increase their R&D expenditures more than others are the ones with higher knowledge stocks (Oil products, Energy intensive industries, other industries and Electricity). The initial impact of the carbon tax diminishes at the end of the period and becomes uniform for all sectors.

Figure 8: Carbon tax impact on knowledge accumulation rates: Net effect with respect to baseline 2005-2050. (In percentage)

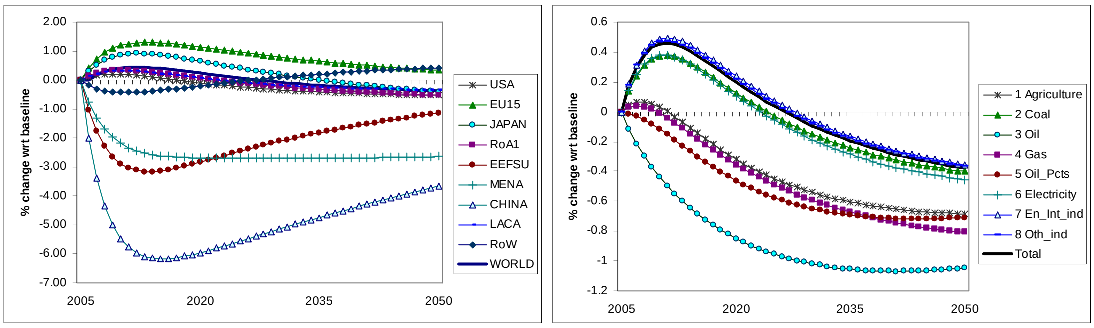


a) EU15 ***b) China***

The case of China shows a completely opposite behaviour. First of all, being a more carbon intensive economy, China suffers more from a carbon tax. In addition, all productive sectors reduce their investments in R&D because of the recessionary effect of the tax, particularly fossil fuels and electricity. However, the negative impact of the tax is reduced in the future allowing the sectors to accumulate more knowledge and gradually recover form the initial policy costs.

Figure 9 presents changes with respect to the baseline scenario on the knowledge stock by region in the left panel and by sector for the entire world in the right panel. The differences on the regional stock of knowledge are very similar to the evolution of the GDP. An interesting result is the redistribution of knowledge accumulation between sectors, particularly within energy commodities, despite the model's specification, which considers R&D investments that generate neutral technical change for every sector (detailed data to identify energy saving R&D investments within every sector was not available). In fact, the carbon tax induces a shift in knowledge investments from carbon-based fuels such as oil, oil products, and gas to the rest of the sectors.

Figure 9: Carbon tax impact on knowledge stocks: Net effect of ETC with respect to baseline 2005-2050. (In percentage)



a) Knowledge stock by region ***b) World knowledge stock by sector***

Even though the coal sector reduces its output in most of the regions, there is a noticeable increase in the R&D investments in the first half of the period. This result is directly related to the increase in output in USA, EU15, and Japan. Finally, it is also interesting to note the effect of the carbon tax in fostering R&D during the first years augmenting the knowledge stock with respect to the baseline, followed by a reduction of the R&D investment rates in the future. As mentioned before, the coal elasticity of supply is one of the factors explaining the increase of its use when the carbon tax is imposed. In addition, this result may be the outcome of an encouragement in R&D investments due to a market effect since coal is an important input in the world economy. The size effect would encourage innovation in the larger input sector, while a price effect would redirect innovation efforts to sectors having higher prices (Acemoglu et al., 2009).

6 Conclusions

The growing concern about the importance of knowledge and technology as a determinant of economic growth and development has provided an impulse to reconsider the role of R&D expenditures in the system of national accounts. One of the main outcomes is the availability of satellite accounts providing a fundamental requirement for knowledge accounting, and moreover, offering the possibility to improve the existing databases and models used to evaluate different kinds of policies. Although currently those R&D satellite accounts are not available for all countries with the same detail, this study collected and used different sources of information on R&D expenditures to extend the GTAP database. This was done to not only include the investments in R&D but also a knowledge stock that is the product of a creation process which also accrues remuneration as a production factor.

The extended database constitutes the main element for modelling endogenous technical change in a multi-sector CGE framework, contrary to the autonomous technical change set exogenously which has been the most used formulation for the modelling exercises with some exceptions. The ETC process takes into account not only knowledge as an additional factor but at the same time allows for the consideration of spillovers following its characteristics of non-rivalry and non (or partial) excludability. To test the new model against the autonomous or exogenous technical change formulation a climate policy based on a uniform carbon tax has been implemented in both formulations.

Including a knowledge stock within the database and model reveals a higher flexibility especially in countries that can accumulate more knowledge. This result is explained because the initial losses due to a carbon tax are reverted in the future thanks to the increased and improved production processes which are the fruit of R&D investments and its spillovers. In contrast to developed countries which are able to react faster to a carbon tax burden and may also increase production; developing regions carrying a higher loss at the beginning can also recover their GDP growth rates as long as they accumulate a significant knowledge stock. Thus, the model with ETC produces a slightly higher cost of climate policies reflected in a lower Gross World Product growth, but in contrast CO_2 emissions reductions are relatively higher translating into an overall outcome of lower carbon intensities with respect to the model without ETC.

There are also some important sectoral effects, which depend on the region and are explained because of the knowledge endowment. The regions that show an increase in GDP due to a higher knowledge stock experience a redistribution of their output, with a decrease on the production of high carbon-based fuels, while the rest of the industries including electricity generation increase their production. On the other hand, developing regions which reduce their GDP also show an output reduction on almost all sectors.

Some sectors show specific trends that might be worth highlighting as a response to a carbon tax. Refined oil products display an increase in production in most regions or relatively lower reductions given that its use is mostly for transport activities, which do not have an explicit alternative fuel for substitution in the model, while coal increases its output during the first years in developed regions. This would follow a market size effect that fosters R&D investments in sectors of a relatively significant size. Finally, agriculture always reduces its production. However, this could be the outcome of the lack of information on R&D expenditures regarding that sector.

The inclusion of a knowledge stock in policy simulations supports the transfer of technology because it could help to reduce the existing gap between regions as well as collaborate to curb emissions at a more accelerated pace given that most developing regions are still in the process of constructing their own stock of knowledge. With specific transfers or incentives to allow those regions to count on (or access to) a higher stock of knowledge, goals such as accelerating development or reducing emissions might be accomplished faster, with the corresponding benefit reaching not only developing countries but the entire world.

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Annex 1:

Table A1: Impact of a carbon tax on aggregate exports by sector and region for 2010: No ETC (% change with respect to baseline)

qxw	1 USA	2 EU15	3 JAPAN	4 RoA1	5 EEFSU	6 MENA	7 CHINA	8 LACA	9 RoW
1 Agriculture	-1.32	-1.49	-4.17	-1.28	1.72	4.10	5.09	-0.74	-1.25
2 Coal	-7.90	-15.07	-20.86	-8.63	-9.31	-14.08	5.32	-8.67	-11.33
3 Oil	-5.19	-3.57	-8.99	-1.48	0.40	-0.73	25.27	-2.26	-2.08
4 Gas	-5.49	-5.57	-27.23	-3.21	-2.70	-1.93	-62.44	-3.92	-3.86
5 Oil_Pcts	-3.17	3.24	-6.47	-1.16	-4.46	-0.63	-13.04	-1.51	1.25
6 Electricity	-14.26	8.53	39.15	0.44	-10.56	2.81	-59.65	14.06	-14.30
7 En_Int_ind	0.01	2.77	3.12	1.40	-4.21	0.76	-12.35	1.97	-0.76
8 Oth_ind	-1.58	-1.16	-2.62	1.01	2.37	8.06	0.37	1.09	0.02

Table A2: Impact of a carbon tax on aggregate exports by sector and region for 2050: No ETC (% change with respect to baseline)

qxw	1 USA	2 EU15	3 JAPAN	4 RoA1	5 EEFSU	6 MENA	7 CHINA	8 LACA	9 RoW
1 Agriculture	-0.51	-1.64	-3.37	-0.46	1.29	4.20	3.69	-0.60	-3.33
2 Coal	-2.41	-11.39	-14.67	-3.29	-6.51	-7.22	-0.54	-5.67	-5.42
3 Oil	-2.82	-1.22	-2.82	-0.27	0.47	0.60	8.52	-0.58	-0.56
4 Gas	-1.81	-2.36	-27.75	-1.35	-1.00	4.21	-26.65	0.08	-3.24
5 Oil_Pcts	-0.66	1.61	-1.97	0.32	-0.92	-0.13	-1.64	-0.46	0.53
6 Electricity	-9.58	5.06	15.45	-7.02	-1.49	2.80	-32.06	7.95	-9.59
7 En_Int_ind	-0.31	1.87	1.23	0.49	-1.33	-0.12	-6.54	0.84	0.27
8 Oth_ind	-1.40	-0.52	-2.07	1.60	1.32	5.66	-1.83	1.72	0.16

Table A3: Impact of a carbon tax on price of exports by sector and region for 2010: No ETC (% change with respect to baseline)

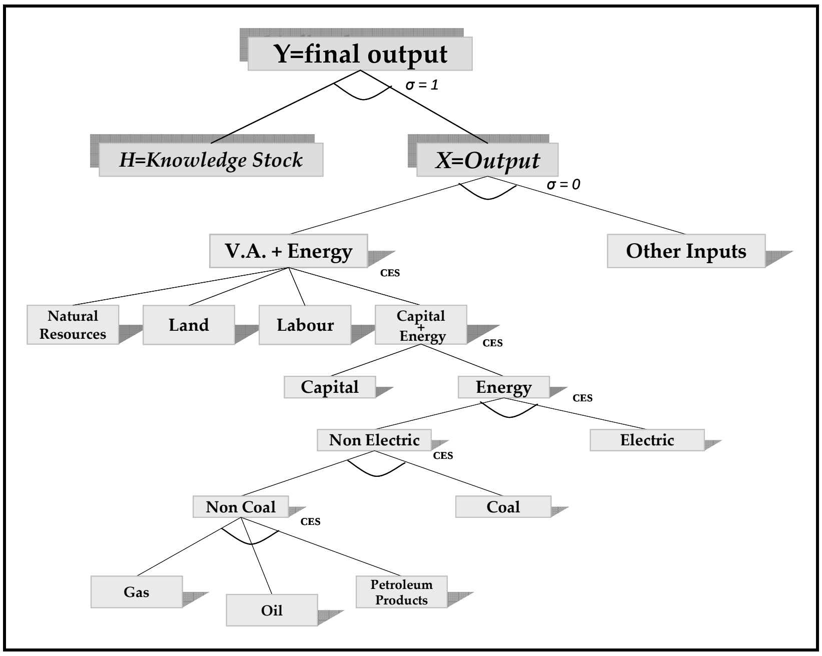
pxw	1 USA	2 EU15	3 JAPAN	4 RoA1	5 EEFSU	6 MENA	7 CHINA	8 LACA	9 RoW
1 Agriculture	0.35	0.78	0.98	0.41	-0.37	-0.97	-0.91	0.36	0.46
2 Coal	-8.42	-6.05	-7.23	-9.00	-8.03	-7.24	-12.59	-7.57	-9.10
3 Oil	-9.62	-9.28	-9.96	-9.78	-10.69	-10.63	-14.18	-9.88	-10.55
4 Gas	-4.94	-5.40	0.50	-5.45	-7.82	-6.66	16.07	-5.16	-5.82
5 Oil_Pcts	-6.44	-7.58	-5.86	-6.52	-6.02	-6.96	-3.85	-6.59	-7.58
6 Electricity	9.21	3.76	3.13	5.89	8.59	5.92	25.15	3.10	9.59
7 En_Int_ind	1.54	0.96	1.35	1.34	2.24	1.44	4.12	1.26	1.93
8 Oth_ind	1.00	0.96	1.13	0.62	0.33	-0.60	0.69	0.60	0.71

Table A4: Impact of a carbon tax on price of exports by sector and region for 2050: No ETC (% change with respect to baseline)

pxw	1 USA	2 EU15	3 JAPAN	4 RoA1	5 EEFSU	6 MENA	7 CHINA	8 LACA	9 RoW
1 Agriculture	0.08	0.52	0.93	0.17	-0.43	-1.24	-0.51	0.12	0.93
2 Coal	-10.82	-8.43	-9.43	-10.93	-9.57	-10.02	-11.68	-9.83	-11.15
3 Oil	-4.79	-4.76	-5.10	-5.00	-5.45	-5.47	-6.61	-4.97	-5.33
4 Gas	-8.09	-7.89	-1.37	-7.98	-9.30	-9.85	-1.91	-8.63	-7.61
5 Oil_Pcts	-4.24	-4.64	-4.21	-4.30	-4.25	-4.49	-4.05	-4.19	-4.70
6 Electricity	5.76	2.30	1.91	4.93	3.48	2.64	10.84	1.35	5.34
7 En_Int_ind	0.98	0.53	0.89	0.86	1.05	0.85	2.21	0.81	0.99
8 Oth_ind	1.06	0.92	1.24	0.61	0.59	-0.20	1.21	0.59	0.85

Annex 2

Figure A1. Nested tree structure for production processes of the modified ICES model



This enhanced version of the model has been also calibrated the substitution elasticity between capital and energy with a lower value than that of the GTAP-E, being set to σ_{KE}=0.25. In addition it considers updated values for the elasticity of supply of fossil fuels, following Beckman et al. (2011), and Burniaux and Oliveira Martins (2000). Supply elasticity of coal is set to 1.1 instead of the range [0.5-0.61], oil is equal to 0.25 instead of [0.5-0.63], and gas is set to 1 instead of [1-18]. The database for this study has been aggregated in 8 sectors and 9 regions as described in the following table:

ICES	
Regions	Sectors
United States	Agriculture
European Union 15	Coal
Japan	Oil
Rest of Annex I	Gas
Eastern Europe & FSU	Oil Product
Middle East and North Africa	Electricity
China	Energy intensive industries
Latin and Central America	Other industries
Rest of the World	