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Climate change policies and endogenous technical change in a general equilibrium modelling framework

Trade Spillovers, Knowledge Stocks and Rebound Effects

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CONTENTS

INTRODUCTION

Scientific research during the last decades has provided evidence to raise concerns about the consequences of a changing climate. In addition, there has been a growing consensus about the contribution of anthropogenic drivers increasing greenhouse gas (GHG) emissions (IPCC, 2007). This has motivated efforts to assess climate change impacts, and subsequently, to consider different alternatives to deal with its consequences. Climate policy plays a fundamental role in proposing instruments to introduce adequate incentives both to mitigate GHG emissions and to adapt to future climate conditions. However, there are several factors that could hamper the effectiveness of the different policies put into practice. Besides the existing difficulties in negotiations to reach a global agreement for a coordinated action, there are also underlying feedback mechanisms that have repercussions on the final policy outcome. This fact calls for careful policy design and assessment to develop a strategy that could bring an effective action to deal with climate change.

The feedback effects that may hinder or amplify the expected result of a policy are mostly related to: i) market-price transmission mechanisms, and ii) the evolution of technical change. Price effects are directly related to the costs of production or consumption activities. Technological change is defined as “improvement in the instructions for mixing together raw materials” (Romer, 1990). It allows increasing production without increasing the required inputs, since it regards the invention, innovation and diffusion of a product or process (Löschel, 2002). A similar concept is technical change, which refers also to an increase in production but that could be the outcome of other factors besides technology, such as a change in organizational structures or economic conditions. Technical change is neutral if it allows producing more with the same distribution of factors. It will be biased if this distribution is modified implying an increasing or decreasing use of a specific factor.

These two feedback mechanisms are closely related. On the one hand, technical change may reduce production costs and allow the diffusion of new or cheaper technologies. On the other hand, price signals can induce the pace of technical change directing innovation to specific (clean) technologies. The literature highlights the role of relative prices, market size effects, and substitution possibilities as important elements of policy induced innovation (Carraro et al., 2010; Löschel, 2002).

The previous considerations provide an idea of how complex the task of climate change policy design and evaluation is. Moreover, they underline the efforts of the research community to: assess climate change impacts (e.g. Bosello et al. 2006, 2007; Tol 2002a, 2002b); and to provide normative insights for mitigation (e.g. Bosetti et al., 2008; Norhdaus, 2008) as well as for adaptation policies (e.g. Bosello et al. 2010).

Motivation

A large body of literature has focused on assessments related to: i) climate policy, ii) international agreements architecture, as well as iii) a variety of mechanisms proposed to deal with climate change. Induced technical change has been extensively studied by means of intertemporal growth optimisation models, including theoretical and numerical exercises (e.g. Smulders and de Nooij, 2003; Nordhaus, 2002; Popp, 2004; Bosetti et al., 2006, Di Maria and van der Werf, 2008). Furthermore, the general equilibrium framework also provides a solid basis for such analysis. There is substantial literature on the general equilibrium effects of different policies considering the inclusion of a carbon price either as a tax or as the price of emission permits in an Emission Trading Scheme (ETS) (see Peterson et al., 2011, for a recent review).

Technological change has emerged as one of the most relevant topics in the climate policy discussion and literature. The importance of technological progress lies in its complexity and the related effects influencing the evolution of future economic and social behaviours. In addition the rebound effect is a closely related topic, which measures how much energy efficiency improvements are offset by actual changes in energy demand. This concept was first introduced by Jevons (1866), and a recent debate has raised concerns about the effectiveness of energy efficiency improvements, which are closely related to climate policies (Dimitropoulos, 2007; Sorrell, 2009). In fact, this effect might emerge as the outcome of price transmission mechanisms as well as feedbacks through induced technical change. As a consequence of the close relationship between these two topics, their analysis becomes a significant issue in the analysis of climate policy effectiveness.

While the effectiveness of climate policies at the international level has been mostly evaluated considering the carbon leakage phenomenon,[1] the literature on the rebound effect has focused on empirical estimates on single-country studies. Consequently, there are three reasons that motivate the development of this thesis. First, the aforementioned price transmission mechanisms may produce significant redistributive effects of the implemented policies. Second, the presence of Endogenous Technical Change (ETC) feedbacks in the analysis may reduce or intensify the initial effects. Third, the analysis of the rebound effect has focused on specific sectors, disregarding the final effect when considering international trade, price, and technology feedback mechanisms among countries.

In this context, computable general equilibrium (CGE) models provide the perfect framework to analyse feedback mechanisms based on relative price signals. However, most of the multi-sector CGE models employed in the literature consider technical change as an exogenous factor; therefore, disregarding policy induced technical change behaviours. Taking into account ETC in policy assessments is a crucial element of the analysis. Most of the analyses considering ETC are based on aggregated growth models (e.g. Nordhaus, 2002; Buonanno et al. 2003, Popp, 2004; Carraro and Galeotti, 2004; and Bosetti et al. 2006). However, there are few multi-sector CGE models with an explicit ETC formulation (Goulder and Schneider, 1999; Sue Wing, 2003; and Otto et al., 2008), even though all of them consider a single country.

Therefore, the most important concepts underlying the structure of this thesis are related to climate policy effectiveness. The first one is ETC, which has been considered through international technology spillovers and the accumulation of a knowledge stock. The second one is the general equilibrium framework, which allows considering market-price feedback mechanisms. The combination of these features in a multi-sector and multi-region recursive dynamic CGE model provides a valuable instrument for the purposes of this study. Moreover, it is a coherent and comprehensive basis to analyse the implications of policies related to a global phenomenon such as climate change.

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[1] Carbon leakage is related to the increase in emissions on countries without an emission reduction target, compared to the reductions achieved on countries with explicit reduction targets.

Research objective and structure of the thesis

The objective of this research effort is to investigate the implications of feedback effects in the implementation of climate policies. Given that climate change is a global problem and that the economic costs of dealing with it will involve all countries, it seems appropriate to analyse this subject in a multi-region and multi-sector framework. This implies considering economic interrelationships both at the regional and the global level taking into account the implications of international trade as well as GHG emissions.

For this purpose, the analysis is based on three chapters, each one focusing on the main concepts cited above and by means of a multiregional CGE model. The general description of the original model used in the three chapters (ICES) is presented in Annex A, while the modifications to the model are detailed in every chapter.

The first chapter focuses on the analysis of technology spillovers embodied in international trade and its implications on economic growth and emissions when a climate policy is implemented in developed countries. Most of the literature has focused on disembodied technological spillovers (e.g. Buonanno et al., 2003; Carraro and Galeotti, 2004; Nagashima and Dellink, R., 2008; Bosetti et al., 2008), while few studies consider trade-embodied spillovers with an endogenous transmission mechanism (Diao et al., 2005; Leimbach and Baumstark, 2010; Hübler, 2011).

The effects of trade spillovers are modelled as increases in capital and energy-biased technical change linked to imports of selected capital goods. This specification reveals redistributive effects both at the regional and sectoral levels. Regions prone to import specific capital goods realise the absorption of foreign technology in higher GDP growth rates. This has a feedback effect increasing carbon leakage since spillovers allow for higher outputs in developing regions with no climate policy. However, regarding climate policy assessment, the net effect of explicitly considering spillovers is relatively small as suggested by previous studies (Bosetti et al., 2008; Leimbach and Baumstark, 2010).

The second chapter deals with knowledge accumulation by extending the CGE model with endogenous technical progress based on research and development. This allows to better account for price-induced behaviours triggered by climate policies. In the related literature, the few existing studies use multi-sector CGE models taking into account knowledge stocks at the national level (Goulder and Schneider, 1999; Sue Wing, 2003; and Otto et al., 2008). This study extends a multi-sector and multi-region CGE model with sector specific knowledge stocks. The extended model is then used to evaluate the net effect of explicitly modelling ETC by implementing a uniform carbon tax. Accounting for knowledge accumulation renders an economy more flexible to price induced signals. In addition, countries with higher knowledge endowments are in a better condition to deal with climate policy costs. This would support specific knowledge or technology transfers to developing regions as an incentive to actively participate in a climate policy agreement.

Finally, the third chapter highlights the concerns regarding a reduced effectiveness of climate policies due to the existence of a rebound effect. Although the rebound effect literature has received important contributions (summarised by Dimitropoulos, 2007; Sorrell, 2007 and Sorrell, 2009), there is a lack of a study considering the effect at the sectoral and regional levels at the same time. The chapter presents an analysis of energy efficiency and carbon tax policies using the modified CGE model that includes knowledge accumulation. Previous studies have only focused on specific sectors or have used single-country CGE models (see Sorrell, 2009 for a review). The paper extends the analysis by including international trade interrelationships embedded in the global CGE. Based on those estimations it is possible to offer some insights about the potential effectiveness of the policies evaluated. Therefore, the existence of economy-wide rebound effects should not be considered as an undermining argument for climate policies. On the contrary, it should be used to select sectors to design and implement those policies according to their potential effectiveness.

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CHAPTER 1: Technology spillovers embodied in international trade: Intertemporal, regional and sectoral effects in a global CGE framework[*]

1.1 Introduction

The relationship between trade and the environment has received increasing attention since the seminal work of Grossman and Kruger (1993). In assessing the environmental effect of the North Free Trade Agreement (NAFTA), they found that the liberalisation in trade between Canada, USA and Mexico could increase environmental quality in Mexico. Copeland and Taylor (2003) developed an interesting theoretical framework to study both aspects of the trade-environment relationship. Not only trade affects environmental quality through a reallocation of production activities, but environmental policy can also influence the choice of plant location, affecting trade flows. Another branch of literature has considered the relationship between trade, technical change, and growth. International trade increases the number and the varieties of inputs and technologies that can be used for domestic production. Moreover, it provides a further channel for the exchange of ideas and thus it increases the opportunities of imitation. As a consequence, international trade can generate international technology spillovers that increase domestic productivity. This is the idea behind the model of endogenous growth with international trade developed by Grossman and Helpman (1991). The existence of international spillovers was empirically supported by the seminal empirical work of Coe and Helpman (1995).

More recently, the interest has been on the intersection between trade and climate change policies. On the one hand, trade barriers can be implemented to address competitiveness concerns raised by climate policy. On the other hand, policies that promote exports and foreign direct investments can increase the transfer of technology and knowledge.

The links between trade, technology, and the environment have been widely studied both in the empirical and theoretical literature. Carraro et al. (2010) offer an extensive review of literature about environmental policy and technical change. Most of the studies have focused

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on disembodied technological spillovers mainly trough R&D and a stock of knowledge (e.g. Buonanno et al., 2003; Carraro and Galeotti, 2004; Nagashima and Dellink, R., 2008; Bosetti et al., 2008). Few studies explicitly account for the potential indirect effect of trade on technical change. For example, Copeland and Taylor (2003) base their analysis on static models, which do not allow for dynamic effects and technology transfers. Grossman and Helpman (1991) consider the dynamic relationship between growth and trade, but they neglect the interactions with the environment. Bayoumi et al. (1999) analyse the influence of R&D and trade on total factor productivity (TFP) in a multicountry macroeconometric model by incorporating previous estimates of R&D spillovers (Coe and Helpman, 1995 and Coe et al., 1997). Their analysis highlights the important contribution of spillovers to growth of both developed and developing countries, but do not include environmental or climate policy concerns.

There are not many studies that include climate policy and embodied technological spillovers (Leimbach and Baumstark, 2010). Similarly, few use multi region and multi sector CGE models considering technology diffusion explicitly through trade (Hübler, 2011). Most of the remaining studies that consider technology spillovers in a multi sector CGE framework emphasise transmission mechanisms of exogenous technology improvements (Van Meijl and Van Tongeren, 1999; Das, 2002; and Andriamananjara and Das, 2006). To the best of our knowledge there are few papers modelling spillovers effects with endogenous mechanisms based on trade flows of a CGE model. Moreover, they share an important limitation in the analysis. Diao et al., (2005) focus on a single-country model, while Hübler, (2011) uses a multi-region model but circumscribes to a policy analysis focusing also on single-country effects.

This paper contributes to the CGE literature by investigating the relationship between trade, technology, and the environment using a multi-sector and multi-region dynamic recursive CGE model. In this context, the main contributions of the paper are: i) to include endogenous factor-biased technical change based on trade flows in a CGE model, particularly for energy and capital, ii) to analyse the implications of specific spillovers embodied in trade of capital goods (machinery and equipment), and iii) to highlight the implications of accounting for indirect effects induced by spillovers. For these purposes, this paper takes advantage of a global trade database to implement spillovers by specifying technology source and destination regions. This allows modelling trade-embodied knowledge transfers in order to analyse the net effects of climate policy both in developed (technology source) and developing (technology recipient) regions.

We find that explicitly modelling trade spillovers reveals significant effects thanks to the transmission mechanisms underlying imports of capital commodities. We then assess the net contribution of modelling trade spillovers within three policy scenarios. The aggregated net effects of spillovers are rather small confirming findings from previous studies. However, we identified important international and intersectoral redistribution effects due to technology transfers represented as embodied spillovers.

The remainder of the paper is structured as follows. Section 2 revises the empirical background on international technology spillovers related with CGE studies. Section 3 describes the inclusion of trade spillovers in the modelling framework. Section 4 introduces the baseline scenario with emphasis on indicators related to spillovers. Section 5 illustrates three policy scenarios including a sensitivity analysis. Finally, section 6 concludes.

1.2 Spillovers empirical background and the CGE literature

International technology spillovers can be categorised in two types: disembodied and embodied. Disembodied international technology spillovers are the flow of ideas that take place without the exchange of commodities. Examples of disembodied spillovers are present through workers' mobility, students exchange programs, international conferences and journals. Embodied international technology spillovers are linked to the exchange of goods, particularly capital goods. The use of new equipment in the manufacturing and industrial sectors is considered an important source of technological progress and thus of economic growth (Jaffe, Newell and Stavins; 2005).

The degree of embodied technological spillovers is related to the level of capital imports, absorptive capacity, education, and knowledge stocks among other determinants. These in turn may depend on country specific policies. Trade within different classes of goods leads to different degrees of knowledge spillovers because technology intensity varies across sectors, leading to different degrees of embodied technology. Technology spillovers are neither automatic nor costless but they require adoption capabilities, e.g. human capital and indigenous research capacity. The absorptive capacity of a country is related to its economic, human, and technological development (Van Meijl and Van Tongeren, 1999).

Several contributions have estimated the effect of both embodied (Coe et al., 1997; Cameron et al., 2005; Madsen, 2007; Badinger and Breuss, 2008; Franco et al., 2010; Seck, 2011) and disembodied (Coe and Helpman, 1995; Bernstein and Mohnen, 1998; Eaton and Kortum, 1996; Keller, 1998; Nadiri, 1993; López-Pueyo et al., 2008) spillovers on total factor productivity. However, the cited studies estimating embodied spillovers do not show an explicit relation between trade and factor-biased technical change. This additional information would allow explicitly modelling the direct influence of international trade on the use of specific factors or inputs.

A first step in this direction is the work by Carraro and De Cian (2009), which estimate the drivers of factor-biased technical change using a Constant Elasticity of Substitution (CES) production function between capital, labour, and energy. Alternative sources of factor-biased growth are tested for each one of the three inputs. The paper finds that capital good imports from OECD countries are an important source of capital and energy factor-biased technical change. An increase in machinery imports from OECD by 1% boosts energy-augmenting technical change by 0.093% and capital-augmenting technical change by 0.027%. OECD countries are considered to be the technology frontier performing most of the global R&D, although emerging economies have been increasingly gaining importance in technology development (Dechezlepretre et al., 2009). As a consequence, the knowledge content of the capital goods they produce is larger than in other countries and therefore they are an important source of technology spillovers. However, that statistical relationship provides a partial measure of technology spillovers, since it does not account for the general equilibrium effects induced by spillovers. When input productivity increases, the factor price decreases and this effect might stimulate the demand of that input, eventually compensating the input-saving effect of spillovers. This adjustment is also known as the rebound effect and it is better analysed in a general equilibrium framework.

More sophisticated approaches that consider the dynamic effects of endogenous technical change on the environment through international spillovers have been proposed by the modelling community in the field of climate change economics. Regarding intertemporal optimisation and integrated assessment models, Bosetti et al. (2008) focus on disembodied energy R&D international spillovers, and conclude that the effects in stabilising costs are rather small, particularly for climate policy analysis. Within the same stream of literature, Leimbach and Baumstark (2010) include endogenous technical change driven by capital trade, R&D investments and technological spillovers in an intertemporal optimisation model to assess climate policy. They find two opposite effects when spillovers are taken into account: i) mitigation costs are increased due to a growth effect, but ii) reduced through energy efficiency improvements. The authors also find that the effects of considering spillovers are moderate and reveal the possibility to intensify and redirect capital trade in such a way to take advantage of the energy-efficiency-enhancing spillovers effect.

In the multi-sector general equilibrium framework, Van Meijl and Van Tongeren (1999) consider trade linkages and sector biased technical change, distinguishing two kinds of embodied spillovers. The first one is based on final good imports, which imply a reverse engineering process that leads to a hicks-neutral improvement for the same sector of the imported commodity. The second one relates to traded intermediate inputs leading to input-bias technical change. The paper focuses on transmission mechanisms based on absorptive capacity and structural similarity, which are present trough trade flows. In the same line of research, Das (2002) analyse the importance of absorptive capacity and structural similarity by implementing technology diffusion from one source region (USA) to the rest of the world. The exercise is based on an improvement in the US heavy industry transmitted as a hicks-neutral improvement in the recipient regions trough international trade flows. In a similar study, Andriamananjara and Das (2006) explore embodied spillovers through exogenous technological improvements using a three region static CGE model based on the GTAP framework. Improvements in the source region spill over to destination regions in the form of Hicks-neutral change affecting TPF in all sectors of the economy. Their analysis is based on bilateral agreements of one country (acting as a hub) with other regions. In particular, it takes into account concepts like absorptive capacity and governance factors to determine the transmission of technology from one country to another through the hub.

The influence of trade openness in technical change is analysed by Diao et al. (2005) with an intertemporal CGE model for Thailand. The study considers two sectors (industry and agriculture) linking labour and land augmenting technical progress to the level of international trade. The embodied spillovers from trade are calibrated to existing empirical evidence, and used to evaluate short and long-run effects of trade liberalisation. One of the conclusions is that trade liberalisation fosters industrial expansion but eventually crowds out foreign spillovers over time.

The effect on carbon leakage derived from international technology spillovers is analysed by Gerlagh and Kuik (2007), by means of two simple models considering firstly international trade on energy-intensive goods and secondly a world integrated carbon-energy market. Both models are then validated with a meta-analysis taking into account results from various CGE studies, concluding that the integrated energy market model describes better the carbon leakage. The paper also modifies a CGE model in order to include endogenous carbon-energy saving technology based on the use of a commodity. It also allows for frictionless technological knowledge spillovers, concluding that carbon leakage decreases in the presence of such spillovers.

Hübler (2011) introduces international technology diffusion of technology through imports and foreign direct investments in a dynamic recursive CGE model, focusing the analysis on China. The study highlights the importance of energy saving technology diffusion for emission reductions. It considers three technology scenarios related to technical progress: i) endogenous progress at the general level, with no energy specific technological progress, ii) adding energy specific endogenous technological progress, and iii) only exogenous technical progress. Then, for the climate policy analysis a specific regime of contraction and convergence is imposed in each one of the three scenarios. Spillovers are present within sectors and also across sectors along the production chain.

In addition to the previous literature, it is worth mentioning recent studies regarding the inclusion of endogenous trade-induced productivity gains, as summarised by Balistreri et al. (2008). Although this literature does not explicitly consider trade spillovers, it considers productivity improvements due to firm heterogeneity. More productive firms would benefit from trade exposure, therefore increasing the productivity of the related industry (Melitz, 2003). These would allow further developments in modelling trade spillovers in the CGE framework, considering the contributions of Ballistreri et al. (2008).

1.3 Modelling International technology spillovers

This paper models embodied spillovers based on international trade of capital goods. The main vehicles of spillovers are machinery and equipment (M&E) commodities. In particular, we consider the endogenous relationship between M&E imports and energy-biased technical change as well as capital-biased technical change. Estimates of the factor-biased technical change due to capital goods imports are drawn from Carraro and De Cian (2009). The model has been calibrated taking into account the influence of machinery and equipment imports only in capital and energy-biased technical change.

1.3.1 The CGE model framework

For this analysis, the relationship between technical change and trade through spillovers has been included in a multi-sector and multi-region CGE model: ICES (Intertemporal Computable Equilibrium System). The model is recursive-dynamic relying on several interaction channels such as international prices as well as capital and trade flows.[2] Technical change in ICES is modelled trough a set of technology parameters. This allows distinguishing factor-use improvements at different levels of the production structure. The generic production function of sector *j* in region *r* can be described by equation (1):

$$Y_{j,r} = A_{j,r} f\left(a_{K,j,r} K_{j,r}, a_{L,j,r} L_{j,r}, a_{E,j,r} E_{j,r}, a_{M,j,r} M_{j,r}\right) \tag{1}$$

where $A_{j,r}$ is total factor productivity, and $a_{i,j,r}$ describes the improvement in a technical change index related to the use of capital, labour, energy, and other intermediate inputs, with *i=K,L,E,M* respectively. In the basic version of the model all these technology parameters are exogenous. By exploiting the empirical relationship between energy/capital productivity and M&E imports from OECD, a partial representation of endogenous technical change driven by trade flows is implemented in ICES.

1.3.2 Calibration of spillovers parameters

To account for spillovers derived from international trade of capital goods we rely on empirical estimates provided by Carraro and De Cian (2009). The choice of this study is

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[2] The description of the ICES model is in Annex A.

based on the following arguments: i) Most of the reviewed studies estimate the effect of embodied spillovers over total factor productivity (Coe et al., 1997; Cameron et al., 2005; Madsen, 2007; Badinger and Breuss, 2008; Franco et al., 2010; Seck, 2011). ii) There is a study providing evidence for factor-specific technological change (Van der Werf, 2008); but that study assumes exogenous technical change and it does not investigate the potential sources, also disregarding international trade effects. iii) Estimates from Carraro and De Cian (2009) take into account the direct relationship between M&E imports and energy and capital-biased technical change. This allows exploiting international trade flows embedded in the CGE model's specification and database.

The estimated coefficients of that study have been obtained through panel estimation with a structural approach, considering a production function based on three inputs (capital, labour and energy). The evidence is based on OECD data taking into account endogenous drivers: R&D expenditures (private and public), M&E imports, and education expenditures (public). Besides providing input substitution elasticities, the study also estimates factor-specific technical change related to the mentioned endogenous drivers.

There are some differences between Carraro and De Cian's specification and the CGE model formulation, which are worth considering. While the empirical evidence is based on a capital, labour, and energy (KLE) specification; the CGE model also takes into account intermediate inputs (KLEM). Bearing in mind this difference, we only considered the parameters that were significant in the empirical estimation that could also be calibrated in the CGE model. This leaves only two parameters, one related to capital and the other related to energy. Although there were also significant estimates for R&D and education expenditures, these variables are not explicit in the CGE model and the database does not report the related specific trade flows.

For this reason, we only concentrate on modifying the model's specification to introduce endogenous technical change based on M&E trade spillovers for capital and energy. In terms of equation (1), the parameters that will become endogenous in the new version are $a_{K,j,r}$ and $a_{E,j,r}$. Therefore, the parameters related to labour and intermediate inputs-biased technical change will remain exogenous.

Because trade flows are endogenous in the model, the formulation in equation (1) allows to isolate the spillovers effects and to define capital and energy-biased technical change as a function of M&E imports. ICES features sectoral and regional imports, which allows the introduction of a relationship between M&E imports from the OECD ($M\&E_{r,OECD}$), and sectoral energy and capital productivity, $a_{i,j,r}$. Thus, the change in factor-biased technical change due to trade spillovers becomes specific for each sector within each region.

$$a_{i,j,r} = \bar{a}_{i,j,r} M\&E_{r,OECD} \qquad i = energy,\ capital \tag{2}$$

The spillovers coefficient, $\bar{a}_{i,j,r}$, represents the sector-specific elasticity of the capital and energy productivity with respect to M&E imports from OECD countries. These coefficients can be calibrated as a function of three variables that determine the propensity of sector *j* in region *r* to benefit from the spillovers driven by trade:

$$\bar{a}_{i,j,r} = a_{0i} CS_{j,r} CR_{r,OECD} MS_r \tag{3}$$

where:

$CS_{j,r}$ = sector *j* machinery imports over total region *r* machinery imports;

$CR_{r,OECD}$ = region *r* machinery imports from OECD/total imports from OECD;

MS_r = share of region r machinery output over world machinery output.

$a_{0i,}$ = calibration coefficient for *i= energy, capital.*

The coefficients in capital letters capture the most important components in determining the final effect of spillovers. $CR_{r,OECD}$ and $CS_{j,r}$ measure both the country's and the sector's propensity to import the spillovers vehicle, respectively. MS_r is an indicator of absorptive capacity. We have chosen this indicator because the M&E sector is the largest importer and user of M&E in most regions. The idea is that the larger the size of the sector that mostly uses the vehicle of technology transfers (M&E), the higher the probability that transfers spill over to the economy of the importing country.

The empirical estimates from Carraro and De Cian (2009) represent average values across regions and over time because they have been obtained using panel data. In addition, equation (3) makes the relationship region and sector specific. In order to replicate the estimates considering the specific characteristics of every region and sector, the parameters a_{0i} have been calibrated to satisfy equation (4). In doing so, the world average of the spillovers coefficient, $\bar{a}_{i,j,r}$ replicates the empirical estimate ($\hat{a}_i$) equal to 0.093 in the case of energy and to 0.027 for capital. For these purposes we have used the data available in the model's database for its calibration year (2001).[3]

$$\frac{\sum_j \sum_r \bar{a}_{i,j,r}}{j * r} = \hat{a}_i \qquad i = energy, capital \qquad (4)$$

Table 1 shows the calibrated values for the spillover coefficients after taking into account the selected coefficients related to absorptive capacity (MS_r) and propensity to import at the sectoral ($CS_{j,r}$) as well as country ($CR_{r,OECD}$) level. Values in bold italics denote significant spillovers that have a higher effect on tradable commodities' output.

Table 1: Calibrated spillover coefficients $\bar{a}_{i,j,r}$ by region and sector

$\bar{a}_{i,j,r}$	*USA*		*JAPAN*		*EU15*		*RoA1*		*CHINA*		*INDIA*		*TE*		*RoW*	
	E	***K***	***E***	***K***	***E***	***K***	***E***	***K***	***E***	***K***	***E***	***K***	***E***	***K***	***E***	***K***
Agriculture	0.013	0.004	0.000	0.000	0.016	0.005	0.005	0.002	0.005	0.002	0.000	0.000	0.007	0.002	0.012	0.003
Coal	0.011	0.003	0.000	0.000	0.001	0.000	0.002	0.001	0.004	0.001	0.001	0.000	0.004	0.001	0.003	0.001
Oil	0.002	0.001	0.000	0.000	0.002	0.001	0.001	0.000	0.005	0.001	0.000	0.000	0.005	0.001	0.036	0.010
Gas	0.001	0.000	0.000	0.000	0.001	0.000	0.006	0.002	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000
Oil_Pcts	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.008	0.002	0.000	0.000	0.000	0.000	0.001	0.000
Electricity	0.011	0.003	0.001	0.000	0.011	0.003	0.002	0.000	0.028	0.008	0.014	0.004	0.006	0.002	0.006	0.002
Chemicals	0.027	0.008	0.001	0.000	0.027	0.008	0.003	0.001	0.024	0.007	0.000	0.000	0.005	0.001	0.013	0.004
MetalProds	***0.119***	***0.035***	0.005	0.001	0.037	0.011	0.006	0.002	0.045	0.013	0.001	0.000	0.008	0.002	0.021	0.006
M&E	***0.407***	***0.118***	***0.207***	***0.060***	***0.510***	***0.148***	***0.097***	***0.028***	***0.276***	***0.080***	0.028	0.008	0.068	0.020	***0.177***	***0.051***
Other Inds.	***0.334***	***0.097***	0.032	0.009	***0.302***	***0.088***	0.062	0.018	***0.193***	***0.056***	0.014	0.004	0.086	0.025	***0.183***	***0.053***
Mrket svices	***0.588***	***0.171***	0.039	0.011	***0.200***	***0.058***	0.053	0.015	***0.266***	***0.077***	0.007	0.002	0.050	0.015	0.077	0.022
Non-mket svices	***0.109***	***0.032***	0.053	0.015	0.080	0.023	0.025	0.007	0.048	0.014	0.000	0.000	0.013	0.004	0.028	0.008
Investment	1.349	0.392	0.437	0.127	1.082	0.314	0.196	0.057	0.653	0.189	0.046	0.013	0.159	0.046	0.561	0.163

The spillovers specification taking into account the calibrated parameters is implemented in ICES using equation (2). According to the empirical estimation, only OECD countries are a source of embodied technology, while all regions can benefit from spillovers. Therefore, the driver of technology spillovers is M&E imports from OECD. In addition, a one-year time lag is assumed to account for the inertia between imports and the effect on factor-biased technical change. As a consequence, an increase in imports at time *t* will have an effect on the factor use in time *t+1*. The time span of the model is 2002 to 2050 with yearly time steps.

The effect of technology spillovers is tied to substitution possibilities among inputs. As discussed in section 4, general equilibrium effects depend on the change in relative prices as

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[3] Simulations on this chapter were performed using the GTAP 6 database, which provides data for the year 2001 (Dimaranan, 2006).

well as substitution possibilities. Technology and substitution are linked with each other and they are often estimated together. Equation (5) shows how technical change and the elasticity of substitution affect the demand of energy, considering growth rates in percentage. Energy demand increases with the scale of the sector's output, given by q_S. The second term describes the substitution effect. An increase in the price of energy p_E compared to the output price p_S reduces the demand of energy. Substitution elasticities with values below one mitigate the price effect, while elasticities greater than one amplify it. An improvement in the productivity of energy, represented by the parameter (af_E) would reduce the factor demand as long as the substitution elasticity is less than one. The lower the substitution possibilities, the lower the rebound effect, and the stronger the effect of technical change.

$$q_E = q_S + \sigma(p_S - p_E) - (1-\sigma) \cdot af_E \tag{5}$$

In the same study, Carraro and De Cian (2009) identified an elasticity of substitution between labour, capital and energy equal to 0.38. For consistency with the estimated coefficients of spillovers, the elasticity between energy and capital has been modified accordingly. An elasticity of substitution with a value lower than unity is supported by many empirical studies. Pindyck (1979) estimated a KLEM formulation for different developed countries, and found values lower than 1 for most of the countries except for Canada and USA. More recently, a low value for this elasticity is supported by Okagawa and Ban (2008), Beckman and Hertel (2009) and Beckman et al. (2011). The last two studies express concerns about the implications of different values for substitution elasticities when evaluating the costs of climate policy and impact assessment of climate change. For this same reason a sensitivity analysis is proposed after the analysis of the selected scenarios with even lower values and also with a higher elasticity (1.5). The main differences are summarised in section 6.

1.3.3 Assessing the propensity to benefit from spillovers

Positive effects of technology spillovers on factors' productivity are not immediate and require adequate absorptive capacities. As suggested by equation (3), the propensity to benefit from spillovers depends not only on the amount of spillover-inducing imported goods ($CS_{j,r}$ and $CR_{r,oecd}$), but also on the absorptive capacity, that is, on the share of M&E output in the economy (MS_r).

Table 2 illustrates the regional shares of machinery output (first column) and the share of imports from OECD in the base year (2001). For instance, India, Rest of Annex I and TE regions have an important share of imports from the OECD, and a very low absorptive capacity, when measured as the relative size of M&E output. As a consequence, imported knowledge is unlikely to spill over to these economies because a small absorptive capacity makes it difficult to exploit the transferred knowledge. Regions that stand to gain the most from spillovers are those characterised by a high absorptive capacity (MS_r), and a large import share ($CR_{,r,OECD}$). These regions are USA, EU15, RoW and China.

Table 2: Propensity to benefit from spillovers

Region	***Regional shares of machinery output in 2001*** MS_r	***Share of machinery imports from OECD over total imports from OECD in 2001*** $CR_{r,OECD}$	***Ratio of machinery Imports on Production***	***Ratio of machinery Exports on Production***
USA	0.30	0.18	0.26	0.21
JPN	0.11	0.12	0.15	0.40
EU15	0.27	0.15	0.49	0.59
RoA1	0.04	0.20	0.79	0.66
CHINA	0.12	0.23	0.28	0.26
INDIA	0.01	0.18	0.28	0.11
TE	0.04	0.21	0.70	0.39
RoW	0.10	0.20	0.88	0.47

The propensity to benefit from spillovers also depends on the general propensity to import, which is an indicator of trade openness. Columns 3 and 4 of table 2 provide additional elements to understand the role of regions as either destination or source. On the one hand, the share of imports over production of M&E in column 3 is a proxy for the propensity to benefit from spillovers showing a particularly large import ratio in the Rest of the World, Rest of Annex I and Transition Economies. On the other hand, the share of exports over production in column 4 shows the regions exporting more knowledge to the rest of the world, namely the OECD countries.

There are clearly two regions that are net exporters of M&E: Japan and EU15, which also have an important share of world supply for M&E. Although the USA exports only 21 % of its production (even less than CHINA), it is the major producer supplying 30% of the world's M&E (first column). Finally, RoA1 shows a specialisation in M&E production since both import and export shares over production are higher than 65%.

Table 3 provides a sectoral picture of trade patterns by region. Sectors that are intensive in machinery imports are M&E, Market Services, and Other Industries, as highlighted in the table. The sector importing more M&E in most regions is the same M&E, except for Row, TE and USA. This information reveals the different potential to benefit from spillovers across sectors. For instance, India has large imports in the M&E sector, Other Industries, and the Electricity industry. China and USA have large imports in Market Services while Japan has them in Non-Market Services. This propensity to benefit from spillovers explains why *ex-ante* spillovers in USA and China could be substantial and why the only visible spillovers effect in India occurs in the M&E and Other Industry sectors. India has a small amount of spillovers because it has a rather low production share and thus absorptive capacity is low as well, as shown in table 1. In contrast, Japan's M&E sector has the biggest share of M&E imports, but overall there are few imports. In fact, Japan is a net exporter of machinery.

Table 3: Propensity to benefit from spillovers – A sectoral perspective

Sectoral imports of machinery $CS_{i,r}$	**USA**	**JPN**	**EU15**	**RoA1**	**CHINA**	**INDIA**	**TE**	**RoW**
Agriculture	0.005	0.000	0.007	0.012	0.003	0.000	0.017	0.011
Coal	0.004	0.000	0.000	0.005	0.002	0.013	0.009	0.003
Oil	0.001	0.000	0.001	0.001	0.003	0.000	0.012	0.032
Gas	0.000	0.000	0.001	0.014	0.000	0.000	0.002	0.001
Oil products	0.000	0.000	0.000	0.001	0.005	0.000	0.000	0.001
Electricity	**0.004**	**0.001**	**0.005**	**0.004**	**0.018**	**0.129**	**0.014**	**0.005**
Chemicals	**0.009**	**0.002**	**0.012**	**0.006**	**0.016**	**0.002**	**0.012**	**0.012**
Metal products	**0.040**	**0.006**	**0.016**	**0.013**	**0.029**	**0.006**	**0.020**	**0.019**
Machinery & Equipment	**0.137**	**0.268**	**0.225**	**0.212**	**0.178**	**0.251**	**0.165**	**0.158**
Other industries	**0.112**	**0.041**	**0.133**	**0.136**	**0.124**	**0.125**	**0.209**	**0.164**
Market services	**0.198**	**0.051**	**0.088**	**0.116**	**0.171**	**0.062**	**0.121**	**0.069**
Non market services	**0.037**	**0.068**	**0.035**	**0.054**	**0.031**	**0.000**	**0.032**	**0.025**
Investments	0.454	0.563	0.477	0.427	0.420	0.412	0.385	0.501

1.4 Spillover stand-alone effects in the baseline scenario

Because the augmenting-technical-change elasticity of energy is larger than that of capital, the statistical effect of spillovers is energy-saving. However, general equilibrium and dynamic interactions may invert that effect through price effects and substitution. The time evolution of spillovers crucially hinges on the time path of machinery imports, which in turn depends on the characteristics of the baseline scenario. Table 4 describes the regional patterns of economic growth, emissions and machinery imports for the period 2001-2050.

Developing countries grow faster than developed ones, contributing to a faster increase in their emissions, which in 2050 account for about 75% of the total. Growth dynamics also explain the larger expansion of imports in developing countries, whose share increase from 44% in 2010 to almost 60% in 2050. The global distribution of machinery production also changes over time, with a reallocation from developed to developing regions.

Table 4: Baseline main indicators

Region	GDP		Machinery & Equipment						CO2 Emissions	
			Production		Imports		Imports from OECD			
	Billion 2001 USD								Gigatonnes of carbon	
	2001	2050	2001	2050	2001	2050	2001	2050	2001	2050
USA	10,082.2	21,478.2	787.5	1,413.0	202.2	447.0	120.8	88.8	1.6	2.7
JPN	4,177.6	6,116.1	295.9	445.9	43.1	108.8	24.5	24.4	0.4	0.4
EU15	7,942.8	14,642.4	704.7	1,091.8	347.8	644.9	293.8	368.7	1.0	1.4
RoA1	1,547.3	3,009.2	110.0	139.9	86.3	165.9	76.8	106.4	0.3	0.5
CHINA	1,603.3	11,934.8	315.2	1,860.2	88.8	330.9	65.4	111.0	1.0	4.5
INDIA	477.3	3,469.0	29.0	170.7	8.2	32.0	6.2	12.4	0.3	1.2
TE	1,011.5	5,142.7	95.3	391.3	66.9	261.1	52.6	142.4	0.9	3.0
RoW	4,436.7	36,506.3	265.9	2,132.9	234.8	1,322.5	177.2	502.7	1.3	6.1
Total	31,278.6	102,298.6	2,603.4	7,645.6	1,078.2	3,313.1	817.3	1,356.7	6.9	19.7

Given the dynamic nature of the model, the size of spillovers also depends on how M&E's trade flows and output change over time. The initial leading role of USA, Japan, and Europe is reverted in 2050, when China and Rest of the World show higher shares of the world's machinery supply. The production of the spillovers vehicle (M&E) becomes more important in the main destination countries: China, India, Rest of the World and Transition Economies. This pattern is independent from the presence of spillovers and it relates to the convergence hypothesis underlying the baseline scenario. Therefore, the gains from spillovers follow a bell-shaped curve increasing at the beginning. As developing countries expand their share of M&E production and exports, the benefits from spillovers should reach a peak to decrease afterwards. Moreover, spillovers augment this trend by generating a virtuous cycle only at the beginning. In fact, the reallocation of production contributes to enhance the absorptive capacity of recipient countries, increasing the potential benefits from technology transfers in those regions. In contrast, the reallocation of M&E output to destination regions reduces the ability to reap the benefits from spillovers at the end of the period. Therefore, the initial source of technology spillovers reduces its share on world production. This trend is also evident when looking at the evolution of imports from OECD for the period 2010 to 2050, as shown on table 5. In fact, total imports from OECD reach a peak in 2040 but start to decline afterwards. The reduction of imports sourced from OECD verifies in almost all regions with the exception of TE and RoW.

Table 5: Total Imports from OECD in Million 2001 USD

Region	USA	JPN	EU15	RoA1	CHINA	INDIA	TE	RoW	Total
2010	117.5	28.2	333.0	89.2	86.2	8.9	75.2	269.0	1007.2
2020	116.5	28.7	357.0	98.2	105.3	10.8	96.4	366.6	1179.5
2030	110.7	27.6	370.8	104.0	115.4	12.1	114.6	449.0	1304.1
2040	100.3	26.0	374.2	106.5	116.4	12.6	129.8	497.0	1362.7
2050	88.8	24.4	368.7	106.4	111.0	12.4	142.4	502.7	1356.7

Increasing spillovers in the Rest of the World, Transition Economies, and China are driven by the continuous expansion of machinery imports in these regions. In fact, fast-growing economies are characterised by expanding their demands, which also drive up the import demand. Both China and India import a large share of M&E from OECD countries. However, spillover effects are less significant in India because of a more limited absorptive capacity (see table 2, first column). Despite the large absorptive capacity that characterise the USA, the increase in imports is quite limited. In fact, this region is a source rather than a recipient of spillovers, probably benefiting more from intraregional spillovers.

Table 6: Capital-biased technical change due to spillovers (% change with respect to 2001)

Region	USA		JPN		EU15		RoA1		CHINA		INDIA		TE		RoW	
afe_spill[Capital**]	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Agriculture	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.1	0.1	0.2	0.0	0.0	0.3	0.5	0.6	1.1
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.2	0.2	0.2
Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.2	0.3	1.5	2.2
Gas	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Oil_Pcts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.1
Electricity	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	1.0	1.4	0.7	1.1	0.2	0.4	0.3	0.7
Chemicals	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.8	1.0	0.0	0.0	0.2	0.4	0.7	1.4
MetalProducs	0.1	0.0	0.0	0.0	0.4	0.4	0.1	0.1	1.5	2.1	0.0	0.0	0.3	0.6	1.2	2.5
Machequip	0.4	0.0	1.7	1.3	5.1	6.4	1.2	1.4	9.9	14.2	1.2	2.1	2.9	6.2	11.6	28.1
Oth_ind	0.3	0.0	0.2	0.2	2.8	3.4	0.7	0.8	6.2	8.1	0.5	0.8	3.4	6.9	10.7	21.2
MServ	0.6	0.0	0.3	0.2	2.0	2.5	0.7	0.9	9.1	12.9	0.3	0.4	2.0	4.4	4.7	9.7
NMServ	0.1	0.0	0.4	0.2	0.7	0.9	0.3	0.4	1.6	2.1	0.0	0.0	0.6	1.3	1.6	3.4

Table 7: Energy-biased technical change due to spillovers (% change with respect to 2001)

Region	USA		JPN		EU15		RoA1		CHINA		INDIA		TE		RoW	
af_spill[EGYl**]	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Agriculture	0.0	0.0	0.0	0.0	0.5	0.6	0.2	0.3	0.5	0.6	0.0	0.0	0.9	1.7	2.2	3.8
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.3	0.4	0.2	0.2	0.5	0.8	0.5	0.8
Oil	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.5	0.6	0.0	0.0	0.6	0.9	5.4	7.9
Gas	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.4
Oil_Pcts	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.9	0.0	0.0	0.0	0.0	0.1	0.2
Electricity	0.0	0.0	0.0	0.0	0.4	0.6	0.1	0.1	3.4	4.8	2.3	3.9	0.8	1.5	1.2	2.3
Chemicals	0.1	0.0	0.0	0.0	0.9	1.1	0.1	0.2	2.7	3.6	0.0	0.0	0.6	1.3	2.5	4.9
MetalProducs	0.4	0.0	0.1	0.1	1.2	1.5	0.3	0.3	5.3	7.3	0.1	0.1	1.1	2.1	4.2	8.7
Machequip	1.5	0.0	6.0	4.4	18.6	24.0	4.1	5.0	38.2	58.1	4.3	7.5	10.3	23.2	45.9	134.5
Oth_ind	1.2	0.0	0.8	0.6	10.0	12.2	2.5	2.9	23.0	30.8	1.8	2.7	12.0	25.7	41.8	94.2
MServ	2.0	0.0	1.1	0.7	7.0	9.0	2.4	3.0	35.2	51.9	0.9	1.5	7.2	16.0	17.1	37.4
NMServ	0.4	0.0	1.2	0.8	2.6	3.1	1.1	1.3	5.5	7.4	0.0	0.0	1.9	4.4	5.8	12.2

The effects of spillovers on capital and energy-biased technical change are shown in tables 6 and 7 respectively for 2025 and 2050. The first columns explain the very low effect on technical change for USA and Japan, which become close to zero in 2050. In addition, the tables show that the higher spillovers effects are in M&E intensive sectors, as long as their imports come from technology source regions. In fact, figures on both tables are the outcome of the spillovers coefficients estimated in the calibration process (see table 1), along with the interaction of M&E imports. Again in the case of USA, is useful to illustrate this interaction. While in table 1 the spillover coefficients for USA are relatively high, especially for M&E

intensive industries, the actual positive effects are very low. This is because USA is one of the main sources of technology and therefore does not import much M&E from the remaining source regions. Conversely, the regions that better exploit this combined effect are China, EU15, and RoW.

The time profile of capital-biased technical change growth rates with respect to the base year (2001) in the sector Other Industries is displayed in figure 1, showing a very similar trend compared to the energy one.[4] Figure 1 provides a good example illustrating the influence of spillovers on the growth rates for both: capital and energy-biased technical change, as well as their impact on economic development. In fact, this is an interesting outcome of considering spillovers explicitly in the model. The decreasing positive effect of spillovers is revealed through the bell shape of capital-biased technical change over time. That shape is more evident for RoA1, EU15, China and India, whilst TE and RoW still benefit from spillovers in 2050.

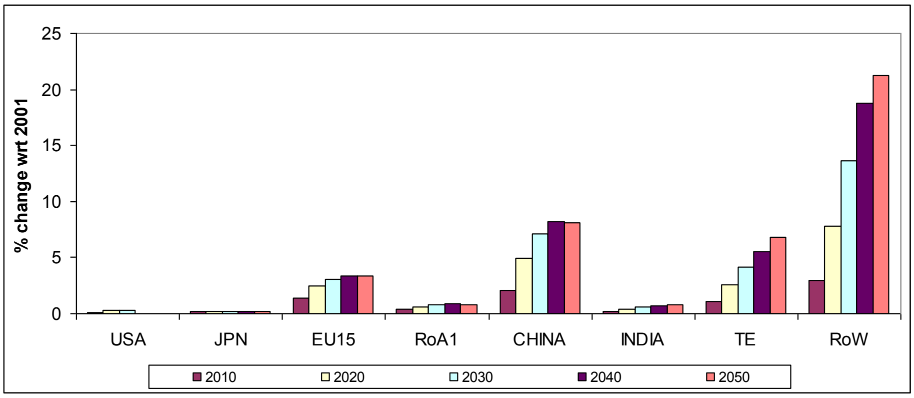

Figure 1: Capital-biased technical change growth in the baseline

In order to assess the implications of trade spillovers on development we compare the new GDP growth with the same variable but in a simulation without spillovers. Thus, we obtain the stand-alone effects, which show redistributive consequences at the regional level, and can be observed in Table 8. When spillovers are active, there is an increase of GDP growth for all regions, except for USA, Japan and India, which reduce their GDP by less than 1% by 2050.

Even though the spillovers effects might be moderate in aggregate terms, sectoral redistributive effects within each region can be substantial. Spillovers trigger a reallocation of

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[4] Although energy and capital-biased technical change show a similar time profile, it is worth remembering that the energy productivity values are much higher given the elasticity with respect to imports of M&E.

resources away from M&E-intensive sectors in all source regions, which is more evident in 2050. Destination regions benefit from spillovers not only by increasing M&E output, but also by increasing most of the remaining sectors' production. For regions like India, where the low absorptive capacity does not allow reaping the benefits of spillovers, variations on sectoral output are rather small and most of them are negative. In addition, source region sectors that are intensive in the spillovers vehicle (M&E) reduce their share in production, which is reallocated to other regions. The positive effect on input-biased technical change is also reflected in a reduction of relative input prices in destination regions, where production is reallocated.

Table 8: Spillover effects by sector in 2050 (% change with respect to a simulation without spillovers)

Region	*USA*	*JPN*	*EU15*	*RoA1*	*CHINA*	*INDIA*	*TE*	*RoW*
GDP	-0.7	-0.9	2.3	0.1	8.7	-0.3	4.5	13.1
CO2 emissions	-1.0	-2.5	-0.8	-1.0	-0.6	-1.2	0.2	2.4
CO2 Intensity	-0.2	-1.6	-3.0	-1.1	-8.6	-0.9	-4.2	-9.5
Agriculture	7.8	12.5	11.7	15.9	4.0	1.2	4.2	4.6
Coal	0.0	0.0	0.0	-0.1	0.1	-0.1	0.0	-0.1
Oil	0.1	0.1	0.0	0.0	0.2	0.1	0.1	0.1
Gas	1.5	-0.8	0.8	-0.1	2.7	-0.6	0.4	1.1
Oil products	-1.6	-2.1	-1.2	-0.9	-0.2	-2.2	-0.4	2.0
Electricity	-0.8	-1.4	0.2	-1.9	4.0	0.8	1.2	3.3
Chemicals	1.7	1.5	3.3	-0.6	9.2	0.3	3.7	12.3
Metal products	-2.6	-1.9	-0.2	-7.4	12.7	0.1	2.9	17.4
Machinery & Equipment	-6.4	-6.2	-3.5	-12.5	11.4	-2.1	1.9	30.3
Other industries	-2.2	-1.4	1.8	-5.9	5.7	-2.9	4.2	14.1
Market services	-0.8	-1.1	2.4	0.0	11.6	-0.8	5.1	15.5
Non market services	0.4	0.0	2.0	1.6	9.4	1.6	4.8	10.0
Investments	-1.3	-1.8	2.6	0.1	8.5	-1.0	5.0	15.5

In the environmental sphere there is a reduction of CO_2 emissions in almost every region. Beside the scale effect, spillovers also induce a technique effect that is confirmed by the reduction in carbon intensity, measured as the volume of CO_2 emissions released in the atmosphere per unit of GDP. The technique effect is much stronger in regions that benefit more from spillovers.

1.5 Environmental, technology, and trade synergies in climate policy

The previous section has described interesting insights about the standalone effects of spillovers and the behaviour of some variables in the baseline. This section considers a set of policy experiments that allow understanding the effect of spillovers on the costs and the effectiveness of environmental policies. For this purpose those experiments will show the effect of two models with identical baselines. The first model has the spillovers mechanism explicitly formulated while the second model replicates exogenously the same energy and capital-biased technical evolution from the first one. This procedure allows comparing the effects with respect to a common reference scenario. Thus, it is possible to isolate the net effect of spillovers due to a specific policy, just by comparing the policy results of both models.

The following analysis focuses on three aspects considering the presence of spillovers in the trade and environment relationship. First, we address the impacts of a simple climate policy based on a carbon tax to reduce CO_2 emissions, which inevitably raises concerns about carbon leakage and competiveness. Second, we consider Border Tax Adjustments (BTAs) in order to deal with competitiveness concerns. Third, we also take into account a trade liberalisation policy, which could foster implicit technology transfers through spillovers.

Policies contemplating BTAs may address leakage and competitiveness concerns by including the carbon tax as a tariff on imported goods. On the contrary, trade liberalisation may reduce carbon leakage indirectly, by increasing the technique effect of spillovers. The most effective option between the two is an empirical issue addressed in the remainder of the paper. For this purpose we analyse the following policy scenarios:

1. ***Climate policy:*** Annex I countries (USA, EU15, RoA1 and TE) impose a domestic uniform carbon tax for a unilateral reduction of CO_2 emissions.
2. ***Climate policy and BTAs:*** The carbon tax is coupled with border trade adjustments to reduce carbon leakage and takes into account competiveness issues. This entails an import tariff based on the carbon content of imported commodities, as described in more detail in the respective section.
3. ***Climate policy and trade liberalisation:*** The same carbon tax in Annex I countries is combined with multilateral trade liberalisation in the spillovers vehicle (M&E) in all regions, removing all import tariffs on M&E.

These three scenarios are compared considering the economic and environmental dimensions. For each scenario we observe changes in regional values of real GDP, CO_2 emissions, carbon intensity of GDP, M&E Production and in the output of selected sectors. The environmental indicator considered is carbon leakage, defined as the ratio of change in emissions in non-constrained countries over emissions in taxed countries.

1.5.1 Climate policy

In this scenario, Annex I regions (USA, EU15, TE, RoA1, JPN) implement a carbon tax levied on CO_2 emissions released by the use and combustion of fossil fuels. The policy contemplates an increasing carbon tax from 2002 onwards, that reaches 55 US$ per tonne of CO_2 in 2050. As expected, there is an indirect cost of implementing such a policy for Annex I regions with reductions of GDP in the range from 0.68% to 5.41% for 2050. Regions with no climate policy increase their GDP as shown on the first two columns of table 9. This is explained by the leakage phenomenon. Given that fossil fuel prices in those regions do not include the carbon tax, they are in a more competitive position due to lower commodity prices. The effect of spillovers is not evenly distributed across countries. For example, spillovers have a null impact on USA, because it is a net source of spillovers. The opposite effect occurs in the EU15 and RoA1, where climate policy costs are slightly larger with spillovers. The reason of these higher costs is because EU15 and RoA1 increase their production thanks to trade spillovers; however, with a higher level of activity the burden of the tax also becomes higher.

Table 9: Climate Policy vs. Baseline: Effects on GDP, CO2 emissions and CO2 intensity in 2050 (in percentage)

Region	***GDP***			***Emissions***			***Carbon intensity***			***M&E Production***		
	No Spillovers	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***
USA	-1.20	-1.19	0.00	-19.58	-19.58	0.00	-18.61	-18.61	0.00	-1.59	-1.67	-0.08
JPN	-0.73	-0.73	-0.01	-12.22	-12.23	-0.02	-11.58	-11.59	-0.01	-1.61	-1.75	-0.14
EU15	-0.68	-0.80	-0.13	-10.69	-10.70	-0.02	-10.08	-9.98	0.10	-1.89	-2.11	-0.22
RoA1	-1.64	-1.69	-0.05	-19.03	-19.04	-0.01	-17.69	-17.65	0.04	0.92	0.72	-0.20
CHINA	1.31	1.22	-0.09	3.27	3.27	0.00	1.94	2.02	0.09	2.16	1.99	-0.17
INDIA	1.54	1.56	0.02	3.75	3.74	-0.01	2.18	2.15	-0.03	3.49	3.54	0.05
TE	-5.41	-6.05	-0.64	-19.33	-19.57	-0.24	-14.71	-14.39	0.33	-8.54	-9.60	-1.06
RoW	1.80	1.99	0.19	5.69	5.79	0.10	3.83	3.73	-0.10	2.53	3.12	0.59

Conversely, Non-Annex I regions tend to gain more with spillovers, given that they are not imposing a climate policy and benefit from the leakage effect. China is an exception that slightly reduces its production when spillovers are active. This is because at the end of the period (2050) they become the major supplier of M&E, at the same time reducing the ability to benefit from spillovers. Remember that according to figure 1, China would be on top of the bell-shaped curve of spillovers' benefits. In addition, there is a combined effect with the contraction of the M&E sector in Annex I countries due to the carbon tax, which also reduces the final spillovers effect. However, at an aggregate level the net effects of explicitly considering spillovers are less than 1% with respect to the baseline (third column). Regarding CO_2 emissions, the outcome is very similar to that of GDP also with a very low net effect of spillovers. Nevertheless, carbon intensity slightly increases in most regions implementing the climate policy, while regions with no climate policy reduce their carbon intensity, except for China.

It is worth analysing what happens at the sectoral level. In particular, net effects on M&E are higher as shown in the last column of table 9. In fact, the impact of the carbon tax is different at the sectoral level. This can also be seen in table 10, which shows the change in output's growth by region after the policy has been implemented. As expected, the most affected sectors are the ones related to fossil fuels in Annex I regions (coal, gas, oil products, electricity, and energy intensive sectors) with a lower contraction in the rest of the sectors. The opposite effect occurs in developing regions that do not have the burden of a climate policy, hence showing an expansion in almost all their sectors. M&E is among the sectors, which face lower negative spillovers due to the carbon tax in Annex I regions. Therefore, although the spillovers potential is reduced, the negative effect is rather insignificant.

Table 10: Variation of sectoral production in 2050 due to the carbon tax (in percentage)

Sector	*USA*	*JPN*	*EU15*	*RoA1*	*CHINA*	*INDIA*	*TE*	*RoW*
Agriculture	0.1	-0.4	-0.6	1.2	0.5	0.5	-3.2	0.4
Coal	-3.8	-2.8	-4.5	-1.7	-1.4	-0.5	-6.6	-1.4
Oil	-0.5	-0.2	-0.3	-0.5	0.0	-0.1	-0.3	-0.1
Gas	-24.4	-38.5	-18.1	-10.0	1.1	0.8	-17.8	-1.1
Oil products	-8.1	-9.2	-0.8	-8.4	2.9	3.6	-10.2	3.7
Electricity	-6.1	-0.7	-3.3	-7.0	4.6	4.1	-14.5	4.4
Chemicals	-3.9	-2.8	-1.2	-4.6	3.0	3.3	-8.9	3.9
Metal products	-2.9	-2.5	-2.0	-5.3	3.1	4.3	-12.2	4.5
Machinery & Equipment	-1.6	-1.6	-1.9	0.9	2.2	3.5	-8.5	2.5
Other industries	-1.7	-1.2	-1.2	-1.4	1.2	1.1	-5.6	1.5
Market services	-1.0	-0.3	-0.5	-2.0	1.6	2.2	-6.2	1.6
Non market services	0.1	-0.2	0.3	-1.1	0.5	0.8	-1.2	0.4
Investments	-1.9	-0.4	-0.7	-2.8	2.4	2.9	-8.4	2.6

Table 11 shows the net effect of spillovers on the output of selected sectors in terms of percentage changes from the baseline. The presence of spillovers tends to amplify the effect induced by the carbon tax, and the net effect on output is negative in most regions and sectors. The only exception is the Rest of the World and some sectors in India. This is due to the fact that India has a low absorptive capacity and RoW is the aggregated region that benefits more from the leakage phenomenon.

Table 11: Climate Policy vs. Baseline: Net effect of spillovers on output of selected sectors by 2050 (in percentage)

Sector	*USA*	*JPN*	*EU15*	*RoA1*	*CHINA*	*INDIA*	*TE*	*RoW*
Metal products	-0.05	-0.07	-0.13	-0.13	-0.13	**0.01**	-0.77	**0.39**
Machinery & Equipment	-0.08	-0.14	-0.22	-0.20	-0.17	**0.05**	-1.06	**0.59**
Other industries	-0.02	-0.02	-0.12	-0.10	-0.06	-0.01	-0.81	**0.21**
Market services	**0.01**	**0.01**	-0.14	-0.05	-0.11	**0.02**	-0.75	**0.21**

Figures from table 11 reveal a redistribution of output, which is higher in developing countries. The carbon tax induces the reallocation of resources to the rest of industries (as seen on table 10). This phenomenon is intensified by the presence of spillovers, although in a reduced way due to the negative net effect on the production of the spillovers vehicle (see last column of table 9).

While the previous analysis provides an idea of the effects on the economic sphere, we now turn to the environmental impacts. A synthetic indicator summarising this information is the carbon leakage ratio computed as the ratio of additional emissions in non-constrained countries over the emissions reduction in constrained ones. Table 12 reports the estimated carbon leakage at different points in time, with and without spillovers. The technical positive net effect of spillovers reducing carbon leakage is only present in the first decade (-0.036%). Then, as developing regions benefit from spillovers their output increases as well as their emissions, leading to slightly higher leakage (0.20%).

Table 12: Climate policy vs. Baseline: Spillovers Net effect (% change with respect to BAU)

Carbon leakage	2010	2020	2030	2040	2050
CL spill	12.29%	22.17%	29.52%	34.36%	38.35%
CL no spill	12.33%	22.17%	29.43%	34.18%	38.14%
Spill effect	-0.036%	0.004%	0.090%	0.181%	0.204%

1.5.2 Climate policy and BTAs

A concern that typically emerges when unilateral environmental policies are discussed is that of environmental dumping or, in the case of climate change, carbon leakage. With stricter environmental regulations in a sub-set of countries, firms tend to reallocate production in countries with lower environmental regulations. In general equilibrium, this effect is induced by the change in relative prices that facilitate reallocation towards regions with a less strict environmental regulation and lower input prices. The use of trade measures as an offsetting mechanism to address competitiveness concerns is a longstanding debate (Brack et al., 2000), which has been renewed recently following the strong EU commitment to unilaterally reduce emissions (European Parliament, 2008).

Until now, the literature has focused on BTAs as one of the policy options that can be implemented to offset competitiveness losses induced by climate policies (Alexeeva-Talebi, et. al, 2008; McKibbing and Wilcoxen, 2008; Veenendaal and Manders, 2008; Fisher and Fox, 2009; Van Asselt and Brewer, 2010). Although it is a measure that addresses the competitive loss, the overall impact and effectiveness are rather low compared to the cost of implementation. In addition, that literature neglects the negative side effect that such measures may have on technology transfers.

The scenario with a BTA policy considers a tariff only to imports from regions which do not have a carbon constraining policy. A very useful concept for this purpose is the carbon intensity, which measures CO_2 emissions per unit of output, in this case using the value of the imported commodity. Actually, it may be very difficult to establish the real level of emissions associated to the production or transformation of a commodity, and thus, its specific carbon intensity. However, all the available information in the database allows computing an average carbon intensity for every sector, and consequently for imports from that region. In other words, it is possible to track CO_2 emissions released during the production of a commodity imported from a region that does not implement the climate policy. Sector and regional carbon intensities are then applied to all imports to estimate their related CO_2 emissions. This would be the most appropriate approach to evaluate the BTA policy option in the CGE model. The level of BTAs is computed multiplying the emissions generated during the production of imported goods by the carbon tax imposed in the importing country. Thus, the BTA tariff is the corresponding percentage of this amount over the import value. This percentage constitutes the additional tariff that should be added to the existing ones.

This is an important issue in order to set a fair tariff related to a coherent climate policy that does not violate the World Trade Organisation rules. Moreover, taxing only the emissions embedded on goods imported from regions that do not have an active climate policy should be the most appropriate method to convey the message of environmental concern through trade policies. Of course, if there are regions with different taxes on emissions, BTAs should also be valid within those regions besides the non-carbon constrained ones, just because of different carbon values. The following results will be analysed taking into account the carbon tax scenario.

Compared to the first policy, BTAs slightly reduce the costs of the carbon tax given that it includes a tariff based on the carbon content of imported goods. However, the differences are rather minor. Due to the fact that BTAs reduce international trade because of import tariffs, the spillovers effects are also lessened. The vehicle of spillovers (M&E) reduces less in relative terms to the carbon tax scenario. This implies that with BTAs, the M&E sector in Annex I countries is less affected, probably favouring the positive spillovers on those countries.

Table 13: Climate Policy with BTAs vs. Baseline: Effects on GDP, CO2 emissions and CO2 intensity in 2050 (in percentage)

Region	***GDP***			***Emissions***			***Carbon intensity***			***M&E Production***		
	No Spillovers	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***	***No Spillovers***	***Spillovers***	***Net effect***
USA	-1.18	-1.18	0.01	-19.53	-19.54	0.00	-18.57	-18.58	0.00	-1.85	-1.86	-0.01
JPN	-0.70	-0.70	0.00	-12.10	-12.10	-0.01	-11.48	-11.48	-0.01	-1.93	-1.99	-0.06
EU15	-0.61	-0.75	-0.14	-10.57	-10.58	-0.01	-10.02	-9.90	0.12	-2.30	-2.47	-0.17
RoA1	-1.58	-1.63	-0.05	-18.94	-18.94	0.00	-17.64	-17.59	0.04	0.41	0.38	-0.04
CHINA	1.26	1.00	-0.26	3.21	3.22	0.00	1.93	2.20	0.27	2.36	1.93	-0.43
INDIA	1.48	1.50	0.02	3.67	3.67	0.00	2.15	2.14	-0.02	3.72	3.78	0.06
TE	-5.37	-6.01	-0.64	-19.26	-19.50	-0.23	-14.69	-14.35	0.34	-8.68	-9.68	-1.01
RoW	1.75	1.82	0.08	5.60	5.68	0.08	3.78	3.78	0.00	2.74	3.13	0.39

Compared to the climate policy results, when the carbon tax is combined with BTAs, there is a stronger contraction of economic activities in most of the sectors within developing countries, particularly China and RoW. Conversely, for Annex I countries the reduction of sectoral output is lower.

Table 14: Climate Policy and BTAs vs. Baseline: Net effect of spillovers on output of selected sectors by 2050 (in percentage)

Sector	***USA***	***JPN***	***EU15***	***RoA1***	***CHINA***	***INDIA***	***TE***	***RoW***
Metal products	-0.02	-0.03	-0.11	-0.02	-0.40	**0.02**	-0.74	**0.23**
Machinery & Equipment	-0.01	-0.06	-0.17	-0.04	-0.43	**0.06**	-1.01	**0.39**
Other industries	-0.01	-0.02	-0.15	-0.04	-0.19	**0.01**	-0.80	**0.09**
Market services	**0.02**	**0.01**	-0.15	-0.05	-0.35	**0.03**	-0.75	**0.07**

As expected, BTAs moderately reduce carbon leakage, compared to the climate policy scenario (table 12), as shown in the first rows of table 15. The increase in productivity abroad allows for more output, and enhances leakage, but in a reduced way as can be seen from the third row in table 15. Although desirable from an environmental point of view, BTAs do not seem to be a good policy option to address leakage in terms of technical change due to the almost negligible effects.

Table 15: Climate policy with BTAs vs. Baseline: Spillovers Net effect (% change with respect to BAU)

Carbon Leakage	**2010**	**2020**	**2030**	**2040**	**2050**
CL spill	11.83%	21.60%	28.93%	33.79%	37.79%
CL no spill	11.84%	21.59%	28.86%	33.65%	37.65%
Spill effect	-0.006%	0.017%	0.077%	0.138%	0.142%
Effects of BTAs on carbon leakage					
Spill	-0.46%	-0.57%	-0.59%	-0.58%	-0.56%
No Spill	-0.49%	-0.58%	-0.57%	-0.54%	-0.50%

1.5.3 Climate policy and trade liberalisation

The recent economic crisis calls for a type of policy, which moves in the exact opposite direction as policymakers may consider promoting a departure from protectionism and trade distortions. Trade liberalisation can be an important instrument to restart global growth, which is currently facing a crisis of final demand. However, it can also have negative consequences on the environment. It might lead to an expansion of economic activities that, in the absence of other policy instruments, could produce a higher level of global emissions. This is a standard result that has emerged from a large set of empirical studies, which however did not consider the technology effect that trade can induce. As shown by some theoretical contributions (Antweiler et al. 2001), the technique effect associated with the expansion in economic activity induced by trade can reduce pollution, with a net positive effect for the environment.

If this effect is not accounted for, an important component of the relationship between trade and the environment is omitted. Though, the magnitude of the spillovers effect is likely to be too small to offset the overall impact of trade on the environment. This result is not surprising considering that a second policy instrument should be used to deal with the environmental problem. Trade liberalisation addresses the distortions created by trade tariffs, whereas a carbon tax or other policies should tackle the environmental problem.

In this section we analyse a scenario that, given the current economic situation and policy debate, could be considered likely to emerge. The same climate policy with a uniform carbon tax on Annex I countries is combined with a multilateral policy aimed at liberalising international trade in machinery and equipment. Results compared to the two previous scenarios show significant differences.

Table 16: Climate and trade liberalisation policy vs. Baseline: Effects on GDP, CO2 emissions and CO2 intensity in 2050 (in percentage)

Region	***GDP***			***Emissions***			***Carbon intensity***			***M&E Production***		
	No Spillovers	*Spillovers*	*Net effect*	*No Spillovers*	*Spillovers*	*Net effect*	*No Spillovers*	*Spillovers*	*Net effect*	*No Spillovers*	*Spillovers*	*Net effect*
USA	-1.22	-1.20	0.01	-19.63	-19.62	0.02	-18.64	-18.64	0.00	-2.92	-3.27	-0.36
JPN	-0.75	-0.73	0.02	-12.34	-12.23	0.11	-11.68	-11.59	0.09	-2.65	-3.09	-0.44
EU15	-0.70	-0.82	-0.12	-10.78	-10.72	0.06	-10.15	-9.98	0.17	-2.11	-2.45	-0.34
RoA1	-1.66	-1.74	-0.09	-19.10	-19.06	0.04	-17.74	-17.63	0.11	-5.61	-6.63	-1.02
CHINA	1.58	4.77	3.19	3.33	3.43	0.10	1.72	-1.28	-3.00	3.51	8.37	4.86
INDIA	1.89	2.34	0.45	3.81	3.80	-0.01	1.88	1.43	-0.45	5.19	5.90	0.72
TE	-5.42	-6.12	-0.70	-19.32	-19.58	-0.26	-14.70	-14.34	0.36	-12.18	-13.25	-1.07
RoW	2.11	2.21	0.09	5.93	6.02	0.09	3.74	3.73	-0.01	5.59	5.62	0.03

Liberalising M&E trade throughout the world increase climate policy costs on Annex I countries as shown on table 16. At the same time, Non-Annex I countries experience higher benefits. In terms of spillovers, this translates in higher net effect for most regions except for RoA1, TE and RoW. CO_2 emissions increase mostly in Non-Annex I countries. However, there is a noticeable technique effect in China and India due to a decrease of their carbon intensities when considering spillovers.

The main positive effect on GDP in China and India is reflected in the increase of M&E production and the rest of the sectors. On the contrary, heavy industries in Annex I countries face a reduction of their output as shown on table 17.

Table 17: Climate Policy and trade liberalisation vs. Baseline: Net effect of spillovers on output of selected sectors by 2050 (in percentage)

Sector	***USA***	***JPN***	***EU15***	***RoA1***	***CHINA***	***INDIA***	***TE***	***RoW***
Metal products	-0.36	-0.44	-0.34	-1.02	**4.86**	**0.72**	-1.07	**0.03**
Machinery & Equipment	-0.68	-1.05	-0.89	-1.53	**5.38**	**1.33**	-1.68	-0.17
Other industries	**0.08**	**0.09**	**0.16**	-0.37	**2.41**	**0.41**	-0.85	**0.16**
Market services	**0.04**	**0.07**	-0.18	-0.12	**4.32**	**0.57**	-0.84	**0.12**

As in the two previous cases, spillovers reduce carbon leakage (-0.19%) only at the beginning of the period with an increasing leakage in 2050 (0.55%, see third line of table 18). The size of spillovers is strictly related to the flow of imports. Trade liberalisation increases the rate of leakage even more, and in the long-run, it is enhanced with spillovers. Trade liberalisation has a scale effect that, besides the adjustments induced by price changes, increases output and thus emissions. When spillovers are taken into account, the scale effect is partially offset by the technique effect reducing emissions in developing regions with no climate policy, but only in the short-term. The contribution of the technique effect is stronger when trade is liberalised.

Table 18: Climate and trade liberalisation policy vs. Baseline: Spillovers Net effect (% change with respect to BAU)

Carbon leakage	**2010**	**2020**	**2030**	**2040**	**2050**
CL spill	12.51%	22.76%	30.54%	35.75%	39.86%
CL no spill	12.69%	22.82%	30.31%	35.24%	39.32%
Spill effect	-0.19%	-0.06%	0.22%	0.51%	0.55%
Effect of trade on carbon leakage					
Spill	0.21%	0.59%	1.02%	1.38%	1.51%
No Spill	0.36%	0.65%	0.88%	1.05%	1.17%

The effects resulting from the three scenarios are summarised in table 19 for the entire simulation period (2001-2050). Trade increases carbon leakage whereas BTAs shows a reduced effectiveness as a measure to address competitiveness concerns. Moreover, this policy has a drawback. It limits the diffusion of technologies through trade, with negative implications for technical change. As already noted by McKibbing and Wilcoxen (2008), BTAs benefits are too small to justify their administrative complexity and trade detrimental effects. On the other hand, trade liberalisation stimulates technology diffusion, which reduce leakage at the beginning but enhances it in the long-run.

Table 19: Summary of policy scenarios: carbon leakage on cumulative emissions 2001-2050

Scenario	Climate policy + BTA	Climate policy only	Climate + trade policy
CL spill	28.89%	29.46%	30.52%
CL no spill	28.79%	29.33%	30.23%
Spill effect	0.101%	0.123%	0.291%

1.5.4 Sensitivity analysis

The size of the elasticity of substitution between energy and capital (σ_{KE}) influences the magnitude of spillovers effects. Whereas the effect of prices is proportional to the elasticity of substitution, the effect of spillovers is proportional to the complement of the elasticity (as shown in equation 5). Therefore, the higher the elasticity, the smaller the spillovers effect, especially in the short-run. This pattern is confirmed by the results described in table 20, which show the net spillovers effect considering different values for σ_{KE}, between 0.25 and 1.5, with 0.38 being the central value. In the extreme case in which the elasticity of substitution between energy and capital is set higher than one ($\sigma=1.5$) the effects of reducing leakage in the first two scenarios are much higher, while the trade policy increases leakage by a much higher amount. In contrast, when the elasticity of substitution is very low ($\sigma=0.25$)*,* this outcome may be reverted in the long-run when considering a trade liberalisation in the vehicle of spillovers. In this case the technique effect leads to an overall reduction in carbon leakage (last column in table 20).

Table 20: Sensitivity analysis on substitution elasticity:
Net spillovers effects on carbon leakage 2001-2050

Elasticity of substitution between capital and energy	Net spillovers effect (% change with respect to BAU)					
Climate policy only	**2010**	**2020**	**2030**	**2040**	**2050**	**2001-2050**
0.25	-0.097%	-0.085%	0.016%	0.189%	0.367%	0.113%
0.3	-0.069%	-0.044%	0.053%	0.202%	0.281%	0.123%
0.38	-0.036%	0.004%	0.090%	0.181%	0.204%	0.123%
1.5	-0.036%	-0.010%	-0.006%	-0.062%	-0.140%	-0.049%
0.38 *	-0.050%	-0.030%	0.028%	0.133%	0.196%	0.081%
Climate policy + BTA	**2010**	**2020**	**2030**	**2040**	**2050**	**2001-2050**
0.25	-0.030%	-0.020%	0.058%	0.199%	0.344%	0.141%
0.3	-0.017%	-0.001%	0.072%	0.191%	0.239%	0.130%
0.38	-0.006%	0.017%	0.077%	0.138%	0.142%	0.101%
1.5	-0.119%	-0.156%	-0.195%	-0.258%	-0.304%	-0.218%
0.38 *	-0.003%	0.014%	0.075%	0.217%	0.339%	0.157%
Climate + trade policy	**2010**	**2020**	**2030**	**2040**	**2050**	**2001-2050**
0.25	-0.439%	-0.475%	-0.223%	0.214%	0.447%	-0.030%
0.3	-0.330%	-0.295%	-0.025%	0.358%	0.476%	0.114%
0.38	-0.186%	-0.060%	0.225%	0.510%	0.545%	0.291%
1.5	0.411%	0.922%	1.352%	1.416%	1.236%	1.194%
0.38 *	-0.319%	-0.317%	-0.203%	-0.267%	-0.453%	-0.297%

* Include a different value for elasticities of supply of fossil fuel: Coal=5, Oil=1 and Gas=4.

The final option of the sensitivity analysis (*σ=0.38**) considers different values for the elasticity of supply of fossil fuels following Burniaux and Oliveira Martins (2000) and Beckman et al. (2011). This allows calibrating those elasticities in order to better replicate some characteristics of the global fossil fuels markets. For the supply elasticities: i) coal is set to 5 instead of the range [0.5-0.61], ii) oil is equal to 1 instead of [0.5-0.63], and iii) gas is set to 4 instead of [1-18]. With higher elasticities of supply, results do not differ much from the initial values. The only difference is that for the climate and trade policy scenario there is a reduction of leakage throughout the entire period. Additionally, leakage rates are one third compared to those with lower elasticities of supply. This is an expected result since the supply elasticity for coal is above 4 (Burniaux and Oliveira Martins, 2000).

1.6 Conclusions

This paper describes the intertemporal and general equilibrium effects of technological spillovers embodied in traded capital commodities. The study focuses on the effects of trade driven spillovers on specific factor-biased technical change. The vehicle of input-biased technical change gains is M&E imports, which shape the use of energy and capital inputs depending on the absorptive capacity of potential recipients.

The use of a dynamic framework highlights an important feature of spillovers that has been neglected by previous literature. Over time, the production of spillover vehicles is reallocated from source regions towards destination regions. In fact, while at the beginning of the simulation period source regions are the main producers of the spillovers vehicle, destination regions become leaders in machinery production by 2050. There are two main elements driving this effect. On the one hand, spillovers boost production in destination regions. On the other hand, the convergence hypothesis underlining the reference scenario assumes higher growth rates for destination countries. The importance of a dynamic analysis is that any region's absorptive capacity is also dynamic and endogenously influenced by other regions. Moreover, given that the source of spillovers is assumed not to change in the future, the rate of diffusion for technology spillovers decreases over time.

The influence of spillovers on growth rates is initially shown on improvements of capital and energy-biased technical change and secondly on output and GDP growth rates. Although there is a reallocation of production and some source regions' GDP might experience a reduction, it is more than compensated by the increase of output in the majority of destination regions, which is also confirmed by the increase in the gross world product. In addition, even though the aggregate effects on GDP growth are moderate, there is a significant redistribution of resources between sectors within the economy. The increases of each sector's energy and capital-biased technical change depend on their own propensity to benefit from spillovers. Regarding environmental concerns, the stand-alone effects of spillovers reveal the importance of a technique effect, which reduces world carbon intensity, with the technique effect much stronger in regions that benefit more from spillovers.

The net effects of embodied spillovers have been evaluated in combination with different climate and trade policies. These are rather moderate at the aggregate level, as found by Leimbach and Baumstark (2010), but show interesting redistributive effects when observed at the sectoral level. Whereas climate policies may trigger carbon leakage, restrictive trade policies have been proposed as a measure to offset emission increases in non-constrained regions. When assessed in the presence of technological effects, BTAs are less effective in offsetting competitiveness concerns because they bring about a second order effect, which generates additional losses due to the reduction in technology transfers. Instead, trade liberalisation, often blamed as damaging for the environment, stimulates technology diffusion, which partially offsets the negative scale impacts, but only in the short-run.

These findings are consistent and robust within a sensitivity analysis on the elasticity of substitution between energy and capital (σ_{KE}). When values are lower than one, spillovers reduce leakage in the short-run because the technique effect prevails. However, the scale effect in the long run increases leakage. Conversely, when values are larger than one, the substitution and scale effects lead to less leakage in both short and long-run when spillovers are explicitly modelled. Only when the trade policy liberalises M&E imports, the scale effect produce a higher leakage for values of σ_{KE} higher than one.

There are some extensions that could enrich the former analysis. A first improvement could be to allow for the possibility to extend the spillovers source regions to not only OECD countries, but other countries as well. This is particularly important, since emerging economies are actually increasing their contribution in technology development, and therefore, it is expected that developing regions will have an important role in the future as a source of technology. This aspect is closely related to the parameter estimation and the corresponding model calibration. Another improvement would be to refine and extend the biased-technical change parameter estimation extending the data to consider both OECD and non-OECD regions, as well as the particular specification of the CGE model. Another interesting development could be also to consider improvements derived from firm heterogeneity that would allow enhancing the trade spillovers representation in a multi-sector and multi-region CGE model.

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CHAPTER 2: Endogenous Technical Change and Climate Policy: Effects of Research and Development and a Stock of Knowledge in a General Equilibrium Framework[*]

2.1 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

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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.

2.2 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).

2.3 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 GTAP 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 Global Trade Assistance and Production (GTAP 7) 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.

2.3.1 Initial considerations and data sources

The task of including a stock of knowledge related to R&D activities in a CGE database must follow the considerations present in the on-going debate about a more appropriate treatment of R&D expenditures, given their close relation to economic development. In fact, these concerns have been taken into account in recent modifications to the System of National Accounts-SNA 2008 (European Commission et al., 2009), which now introduces the treatment of expenditure on R&D as capital formation.[5] This was also the outcome of the efforts to: i) produce R&D statistics and also satellite accounts following guidelines such as the Frascati Manual (OECD 2002), ii) evaluate the effects on national income and GDP of introducing R&D in the national accounts (Fraumeni & Okubo, 2005 and Evans et al., 2009), and iii) offer proposals to provide a bridge between the SNA and the Frascati Manual (Robbins, 2006).

Before the aforementioned modifications to the SNA were taken into account, expenditures on R&D were mainly considered as current expenditure. The main implication of the reclassification of R&D expenditures as investments is that it has effects on accounts such as GDP, savings, investments, and the explicit formulation of a stock of knowledge, which accrues returns from R&D activities.[6] Consequently, expenditures on R&D are already present in the GTAP database (in particular in the OBS sector - Business services nec).[7] However, they have to be reclassified accordingly using reliable sources before capitalising those expenditures in order to estimate the correspondent stock of knowledge. There are many sources of R&D expenditure data, which have been used for this task depending on the detailed degree of information required as shown in Table 1.

The main sources for Gross Domestic Expenditures on R&D (GERD) as a share of GDP are UNESCO (2010) and the World Bank (2010) with very similar figures. UNESCO also publishes GERD by sector of performance and by source of funding. The first classification is divided into five categories: i) business enterprise, ii) government, iii) higher education, iv) private non-profit and v) not specified. The second classification has a sixth category: vi) abroad, as a source of funding. This study uses the first classification (sector of performance) for four reasons. First, there is more available data. Second, it is more appropriate in

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[5] Nevertheless, the SNA 2008 recognises that there are still several issues to be addressed regarding measures and guidelines, which will provide an appropriate measure of R&D. For this purpose a handbook has been published providing guidelines for intellectual property products (OECD 2010).

[6] A summary of the effects of considering R&D expenditures as investments can be found in Fraumeni and Okubo (2005), table 8.3.

[7] This follows from the description of sectors of the database in Narayanan and Walmsley (2008).

correspondence with the SNA since "the unit which 'performs' R&D also 'produces' it".[8] Third, the first classification is suited for attributing and extracting R&D expenditures from the original OBS sector in the GTAP database taking into account intermediate consumption for business enterprise R&D (BERD) and final users (government and others – private non-profit and higher education). Lastly, attributing the share corresponding to the category "abroad" between the other categories could prove to be difficult and would imply modifying the international trade transactions in the database, which could become very intricate.

Table 1: Research and Development data used in this study

Source	Dataset	Indicator
UNESCO	R&D expenditure (GERD)	- Gross domestic expenditure on R&D - GERD (% of GDP) - GERD by sector of performance
World Bank	World Development Indicators (WDI)	- Research and development expenditure (% of GDP)
OECD	Analytical Business Enterprise Research and Development (ANBERD) database 2009	- Research and Development Expenditure by type of industry
IEA	Energy Technology R&D Statistics	- Research and Development Budget - Edition 2009

The most detailed R&D dataset is the Analytical Business Enterprise R&D (ANBERD) database (OECD, 2009) which offers a rather comprehensive breakdown for several industrial sectors for a set of 38 countries. The Energy Technology R&D Statistics are a good source of government energy technology R&D budgets that can be also used to complement the ANBERD data, which is not very detailed in energy sectors.

2.3.2 Constructing satellite R&D expenditures data for the GTAP database

Using the GERD data as a percentage of GDP to compute values for each country and macro region of the GTAP database is the first step to provide the regional total which will be distributed among the industries according to the information present in the OECD-ANBERD and IEA datasets. The second step is to use data from UNESCO (2010) for GERD by sector of performance in order to calculate the distribution for three aggregate sectors: industries (GERD performed by business enterprise or BERD), government (GERD performed by the government), and other R&D (GERD performed by private non-profit and higher education). The category "not specified" was added to BERD, while missing data was imputed according

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[8] OECD (2002), Annex 3: The treatment of R&D in the United Nations System of National Accounts. par. 28, p. 179.

to the average values trying to respect as much as possible the originally available information.

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.[9] 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.[10]

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.

It is worth noting that the ANBERD data relates to business enterprise R&D and that the shares obtained were applied to the fraction of total GERD, which corresponds to the intermediate consumption matrices of the GTAP database. Regarding the remaining sectors of

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[9] 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.

[10] The correspondence between sectors in the GTAP and the ANBERD datasets has been elaborated following the ISIC Revision 3.1 (United Nations, 2002) and is detailed in Annex 1.

performance, their respective R&D expenditures were computed according to the shares from the UNESCO database grouped as public R&D and other R&D expenditure. These remaining sectors were distributed according to the value added share of GDP in every sector within every region.

While this procedure produces a value for the R&D expenditures performed by every sector of the GTAP database, it does not guarantee that it will be lower than the original value of the OBS sector. When R&D expenditure data was higher than the total of the original OBS sector, it was adjusted in such a way that R&D expenditure for that particular sector is equal to 85% of the original OBS value. Furthermore, to maintain the total R&D expenditure in every region, the reduction in that sector was distributed among the remaining sectors. The final outcome of this initial 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.

2.3.3 Including the stock of knowledge

A reclassification of R&D expenditures as knowledge capital formation in the GTAP database is not a straightforward task given that there are some balances that must be maintained. 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 OBS 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. Therefore, the Splitcom program (Horridge, 2008), which allows disaggregating an original GTAP sector given the shares of the new sectors to be created was a very useful tool in this process.

This procedure is an intermediate step that can be described as the creation of a fictitious R&D sector, which does not export or import R&D but produces and trades it domestically. It is useful to identify and isolate the domestic flows of R&D for its reclassification from the intermediate consumption matrix without affecting those of the rest of the database sectors. The process starts by using the value of R&D expenditures prepared previously to compute the corresponding shares of the OBS sector. The necessary information is then provided to Splitcom to reclassify the R&D flows in the database as remunerations to the use of the new endowment (stock of knowledge). 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: $\boldsymbol{\delta}$ is the depreciation rate set to 20%,[11] $\boldsymbol{g_{i,r}}$ is the growth rate computed as the average growth of each GTAP sector output from 1997 to 2004,[12] and $\boldsymbol{r_r}$ 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.[13] 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.

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[11] 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.

[12] 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%.

[13] 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.

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

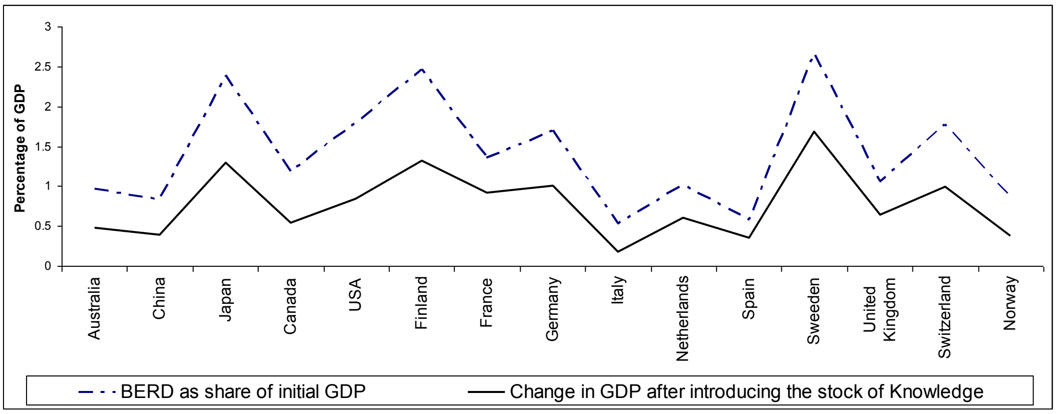
$$Know\_Stock_{i,r} = \frac{INV\_R\&D_{i,r}}{\delta + g_{i,r}}$$

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.

The outcome at this point is a new database that includes the stock of knowledge and its related flows, but that is not balanced yet. There are some imbalances that should be corrected since every sector has an additional investment and endowment. On the one hand, when comparing industry costs against the sales of commodities produced domestically, the highest differences are found in the costs of the original OBS sector given that the previous procedure did not modify factor remunerations and therefore domestic sales are now lower than costs. On the other hand, the rest of the sectors have additional sales (the new investments in R&D), which are partially compensated by remunerations to the R&D endowment.

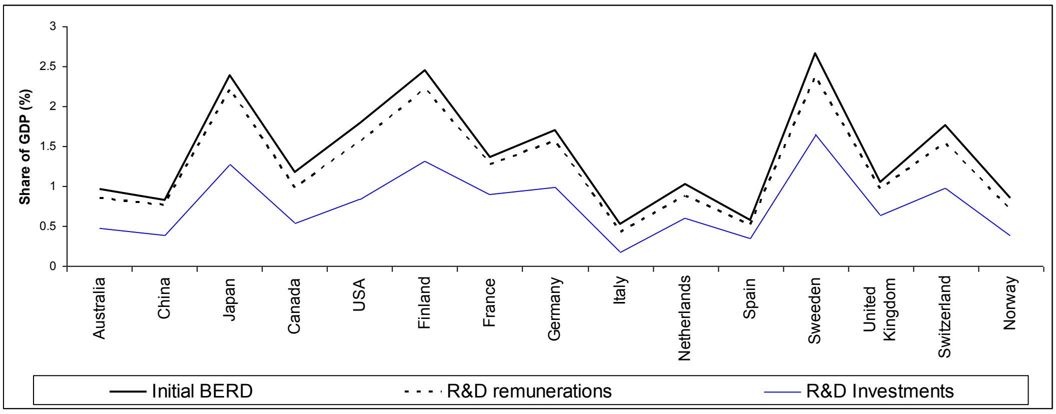
To compensate these differences, the first balance procedure is to distribute the excess costs, which arise due to the unmodified endowment values in the OBS sector, to the rest of the sectors in such a way that the initial differences are reduced by a significant amount. One of the last balancing steps is to adjust the remaining differences by modifying factor remunerations (labour and capital) according to their shares, to maintain the initial labour-capital ratio. After this process the new database should be balanced. Finally, the savings account should also increase because of the additional net regional R&D. 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).[14] 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.

Figure 2: R&D expenditures in the new 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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[14] See Fraumeni & Okubo (2005) p. 283.

2.4 *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).

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

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

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

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).[15] Knowledge stocks accumulate with new investments in the form of R&D expenditures, $R_{i,t}$, less the corresponding depreciation of the existing stock ($\delta^H = 0.2$).

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

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[15] 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.

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. The model used for this comparison is ICES (Intertemporal Computable Equilibrium System), which is based on 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.

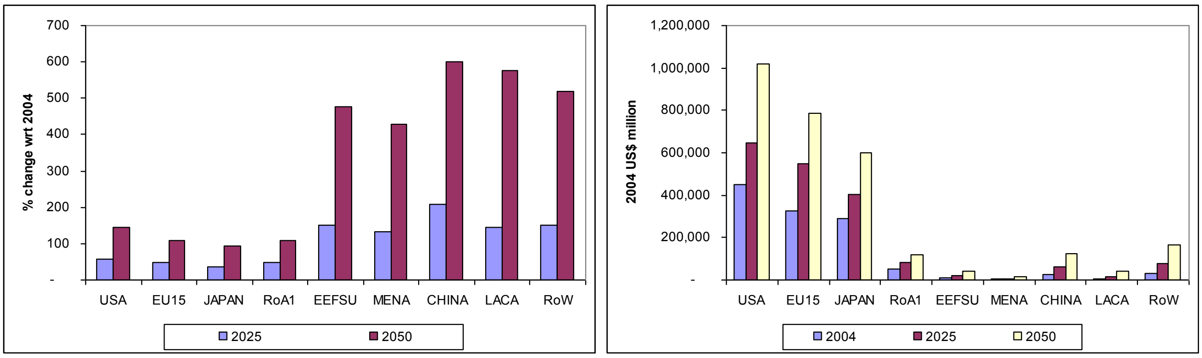
2.5 Simulation results

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

2.5.1 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.

2.5.2 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[16] of 25 and 50 US$ per ton of carbon[17] throughout

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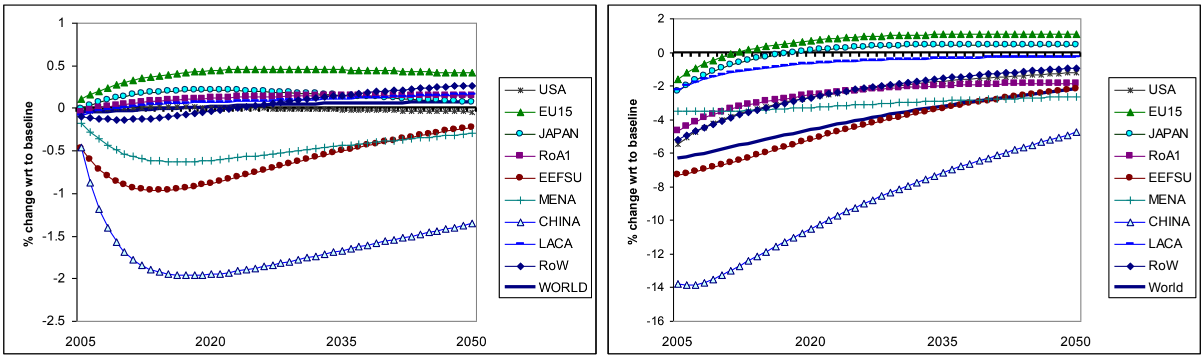
[16] The climate policy in ICES is simulated by introducing a tax on CO_2 emissions related to the use of fossil fuels. It is basically modelled as a tax levied on the carbon content of each fuel (coal, oil, gas and oil products), which is released to the atmosphere through combustion during an economic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

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 from energy intensive industries, particularly in developed regions. In addition, export prices of those industries increase with respect to the baseline case.[18] 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

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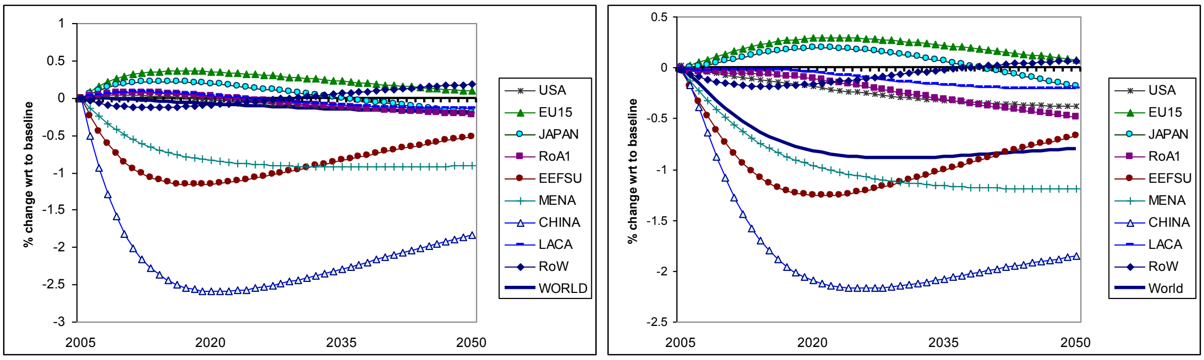
[17] The first value was set as in Goulder & Schneider (1999) to compare their qualitative findings. They are equivalent approximately to 7 US$ and 14 US$ per ton of CO_2 respectively. Regarding our simulation results for both carbon prices, results are qualitatively similar with the only difference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

[18] 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.

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 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.

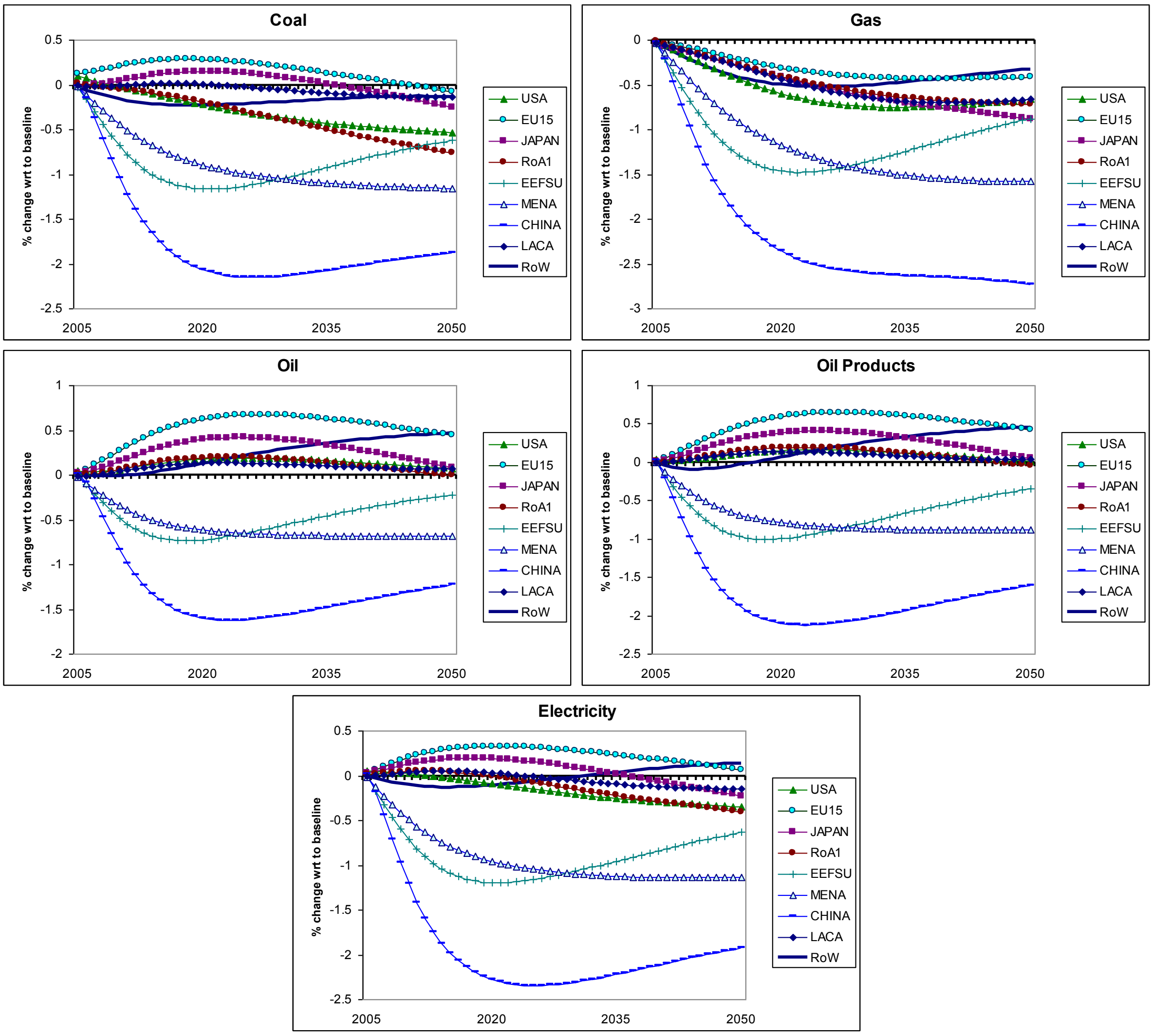
In particular, this outcome can be observed for China, Eastern Europe and Former Soviet Union (EEFSU) and the Rest of the World (ROW) whereas Middle East and North Africa (MENA), which have lower knowledge stocks, do not notice a reduction of that breach before 2035. Nonetheless, the pace of the gap's 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

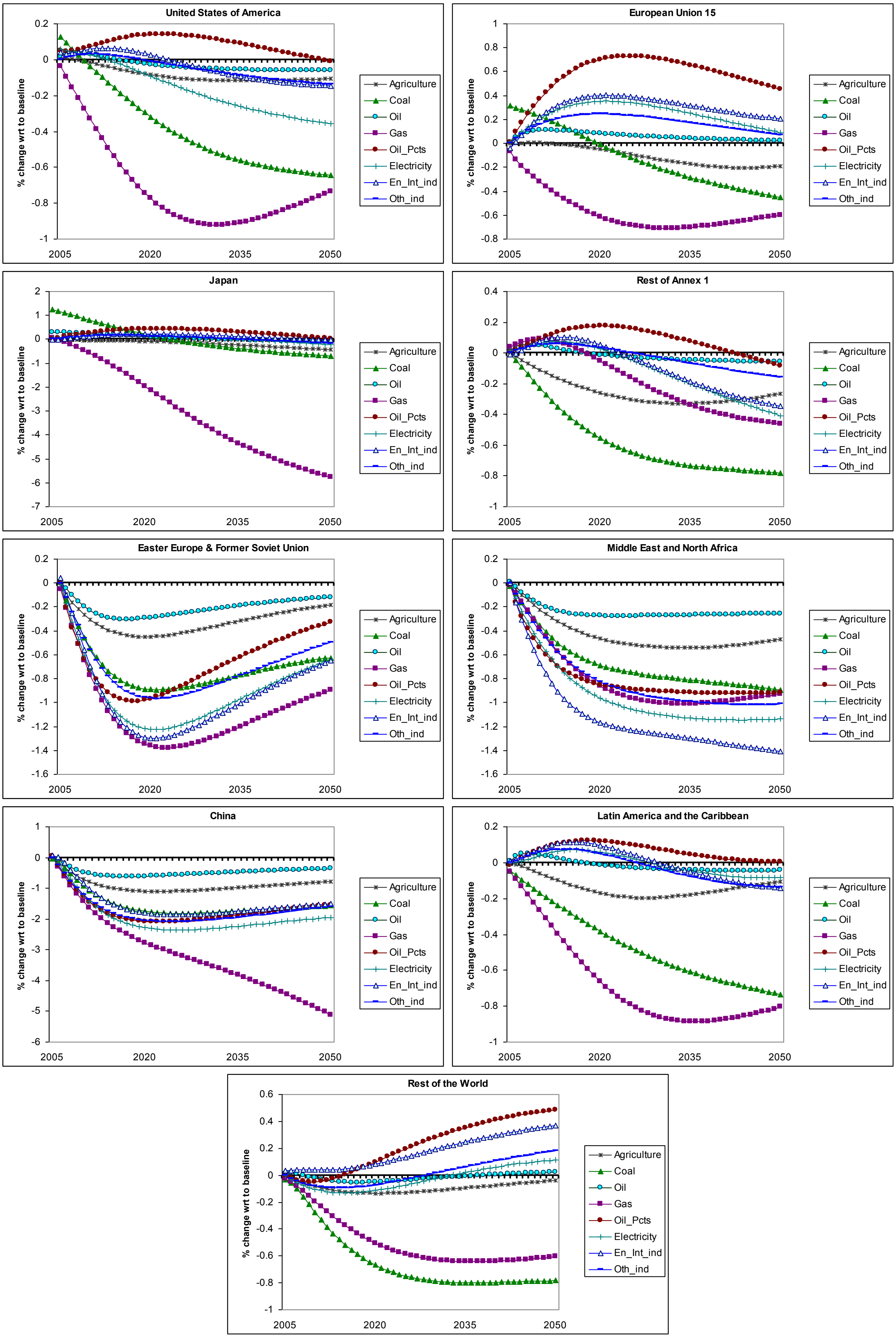
Japan (0.20%) with a peak in 2020. This could be regarded as a rebound effect to the carbon tax, given an increase in energy use in some fuels. The final ETC effect is an overall reduction of world CO_2 emissions by -0.90%, and comparing this variation with that of GDP the ETC formulation shows lower 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.

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



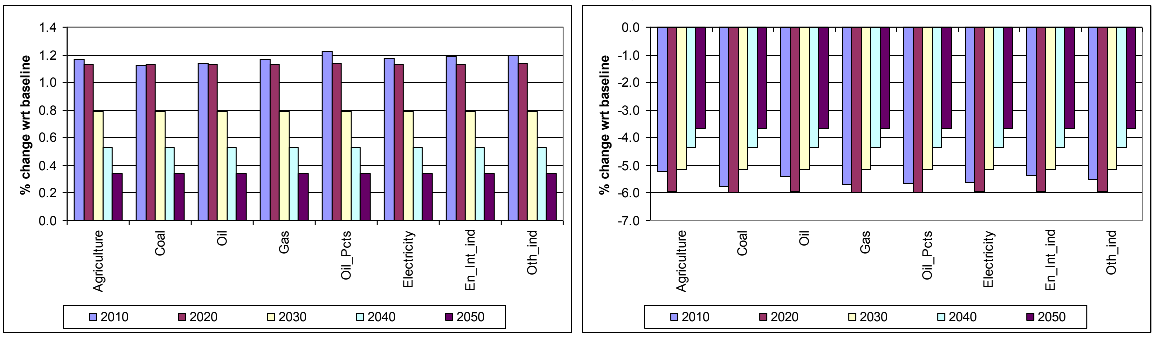
Effects on GDP can be better understood by observing the variation in output of the different industries shown in Figure 7 as difference between the ETC and no-ETC specifications. In this context and before analysing them in detail it is worth mentioning the findings of Goulder and Schneider (1999) when 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.

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)

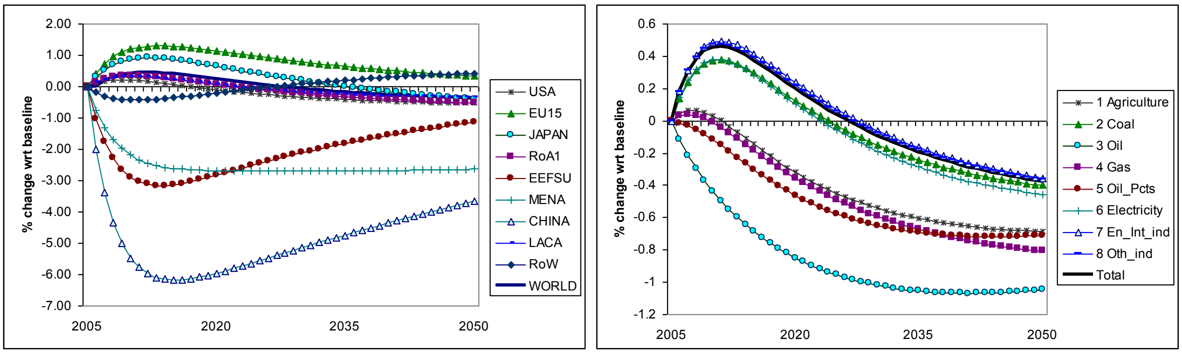


a) EU15 ***b) China***

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)



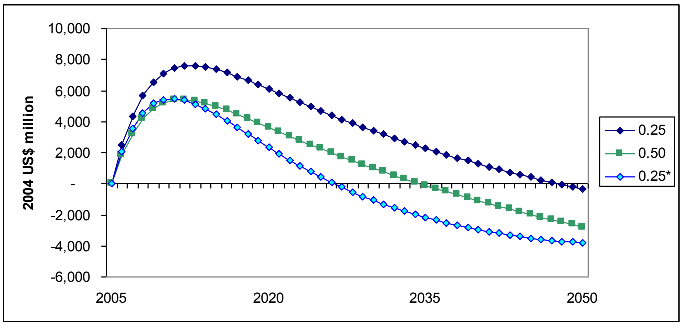
a) Knowledge stock by region ***b) World knowledge stock by sector***

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).

2.5.3 Sensitivity analysis

Since the focus of the policy exercise is to understand the implication taking into account a stock of knowledge that changes endogenously according to the market price signals, we consider a sensitivity analysis on the accumulation of world knowledge stocks when the carbon price is introduced in the model. For this purpose, figure 10 shows the changes in the world's knowledge stock as a result of the induced R&D investments in every sector taking into account discounted differences with respect to the baseline considering a discount rate of 3%.

Figure 10: Discounted carbon tax impact on knowledge stocks



The three paths are produced by different values for the elasticity of substitution between energy and capital. The first one (σ=0.25*) corresponds to the elasticities used throughout this paper with a lower value for capital and energy substitution and elasticities of supply for fossil fuels following Burniaux and Troung (2002), Burniaux and Oliveira Martins, (2000) and Beckman et al. (2011), as detailed in annex 2. The other values disregard the calibration of supply elasticities considering a more rigid supply for liquid fuels and focuses only on the capital-energy elasticity with a lower value (σ=0.25), according to recent literature (Okagawa and Ban, 2008; Carraro and De Cian, 2009; and Beckman et al. 2011). The last value (σ=0.50) was the most used elasticity in the CGE models with a production nest based on a capital-energy composite (Burniaux and Troung, 2002 and Burniaux and Oliveira Martins, 2000).

In the three cases there is an increase in the knowledge stock accumulation due to the carbon tax, which is higher at the beginning of the period and becomes negative towards the end. A higher substitutability between capital and energy reduces knowledge accumulation following a carbon tax (σ=0.50 vs. σ=0.25). With a higher value for σ, it is easier to substitute the costly energy inputs with capital at a lower nest. Therefore, it should not be necessary to use more knowledge to substitute with the rest of the output at the top level. Moreover, if the supply elasticities for liquid fuels are lower, this will produce even lower knowledge accumulation that becomes negative in the middle of the period. In fact, the combination of rigid liquid fuel markets with the recessionary effect of the tax discourages R&D investments particularly after 2015. The net present value over the entire period for the incremental capital stock is 65 US billion for σ=0.50; 168 US billion for σ=0.25 and only 8 US billion for σ=0.25*. This last scenario corresponds to the entire set of parameters used in the simulation results within the previous sections of this paper.

2.6 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, because carbon-based fuel sectors are the ones that reduce their production the least.

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.

A sensitivity analysis suggests that knowledge accumulates less when capital-energy substitution is higher. In addition, when liquid fuel markets are more rigid, R&D investments are discouraged also implying a lower stock of knowledge for the same capital-energy substitution value.

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.

Regarding further developments of the model, an interesting extension would be including intersectoral and international knowledge spillovers. A crucial aspect is the parameter estimation for inter-industry spillovers that depend on the empirical model estimation, which could consider the exposure not only to domestic but also to foreign stocks of knowledge.

Another improvement regards extending the model’s database to consider renewable energies, which could offer more flexibility for assessing climate and energy policies.

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Annex 1: Correspondence between GTAP sectors and those in the ANBERD database

ANBERD classification		*GSC2 Sectors Defined by Reference to the ISIC, Rev.3*			
ISIC Revision 3.1		***GTAP***	***Code***	***Code***	***Description***
15...37	TOTAL MANUFACTURING				
15+16	Food products, beverages and tobacco				
15	Food products and beverages	14	fsh	15	Hunting, trapping and game propagation including related service activities
16	Tobacco products	n.a.	n.a.	n.a.	n.a.
17...19	Textiles, textile products, leather and footwear				
17	Textiles	27	tex	17	Manufacture of textiles
18	Wearing apparel and fur	28	wap	18	Manufacture of wearing apparel; dressing and dyeing of fur
19	Leather, leather products and footwear	29	lea	19	Tan and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
20...22	Wood, paper, printing, publishing				
20	Wood and cork (except furniture)	30	lum	20	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
21+22	Pulp, paper products, printing and publishing	31	ppp	21	Manufacture of paper and paper products
21	Paper and paper products	31	ppp	21	Manufacture of paper and paper products
22	Publish., printing and reprod. of recorded med.	31	ppp	21	Manufacture of paper and paper products
23...25	Chemical, rubber, plastics and fuel products				
23	Coke, refined petrol. prod. and nuclear fuel	32	p_c	231	Manufacture of coke oven products
24	Chemicals and chemical products	33	crp	241	Manufacture of basic chemicals
24-2423	Chemicals excluding pharmaceuticals	33	crp	241	Manufacture of basic chemicals
2423	Pharmaceuticals	33	crp	241	Manufacture of basic chemicals
24xx	Other adjusted	33	crp	241	Manufacture of basic chemicals
25	Rubber and plastics products	33	crp	241	Manufacture of basic chemicals
26	Other non-metallic mineral products	34	nmm	26	Manufacture of other non-metallic mineral products
27	Basic metals	35	i_s	271	Manufacture of basic iron and steel
271+2731	Iron and steel	35	i_s	271	Manufacture of basic iron and steel
272+2732	Non-ferrous metals	36	nfm	272	Manufacture of basic precious and non-ferrous metals
28	Fabricated metal prod. (exc. mach, and equip.)	37	fmp	28	Manufacture of fabricated metal products, except machinery and equipment
29...35	Machinery and equip., instrum. and transp. eq.				
29	Machinery and equipment nec	41	ome	29	Manufacture of machinery and equipment n.e.c.
30	Office, accounting and computing machinery	40	ele	30	Manufacture of office, accounting and computing machinery
31	Electrical machinery and apparatus nec	41	ome	29	Manufacture of machinery and equipment n.e.c.
32	Radio, TV and communication equipment	40	ele	30	Manufacture of office, accounting and computing machinery
321	Electronic valves, tubes and components	40	ele	30	Manufacture of office, accounting and computing machinery
32-321	Radio, TV and communication equipment nec	40	ele	30	Manufacture of office, accounting and computing machinery
33	Instruments, watches and clocks	41	ome	29	Manufacture of machinery and equipment n.e.c.
34	Motor Vehicles	38	mvh	34	Manufacture of motor vehicles, trailers and semi-trailers
35	Other transport equipment	39	otn	35	Manufacture of other transport equipment
351	Building and repairing of ships and boats	39	otn	35	Manufacture of other transport equipment
353	Aircraft and spacecraft	39	otn	35	Manufacture of other transport equipment
352+359	Railroad and other transport equipment nec	39	otn	35	Manufacture of other transport equipment
36	Furniture, manufacturing nec	42	omf	36	Manufacturing n.e.c.
361	Furniture	42	omf	36	Manufacturing n.e.c.
369	Manufacturing nec	42	omf	36	Manufacturing n.e.c.
37	Recycling	42	omf	36	Manufacturing n.e.c.
40+41	ELECTRICITY, GAS & WATER	43	ely	401	Production, collection and distribution of electricity
45	CONSTRUCTION	46	cns	45	Construction
50...99	TOTAL SERVICES				
50...52	Wholesale and retail trade, repairs	47	trd	50	Sales, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel
55	Hotels and restaurants	47	trd	50	Sales, maintenance and repair of motor vehicles and motorcycles; retail sale of automotive fuel
60...64	Transport, storage and communications	48	otp	60	Land transport; transport via pipelines
642	Telecommunications	51	cmn	64	Post and telecommunications
65...67	Financial intermediation	52	ofi	65	Financial intermediation, except insurance and pension funding
		53	isr	66	Insurance and pension funding, except compulsory social security
70...74	Real estate, renting and business activities	54	obs	K	Real estate, renting and business activities
72	Computer and related activities	54	obs	K	Real estate, renting and business activities
722	Software consultancy and supply	54	obs	K	Real estate, renting and business activities
72-722	Other computer and related activities nec	54	obs	K	Real estate, renting and business activities
73	Research and development	54	obs	K	Real estate, renting and business activities
74	Other business activities	54	obs	K	Real estate, renting and business activities
75...99	Community, social and personal services	56	osg	75	Public administration and defense; compulsory social security
01...99	TOTAL BUSINESS ENTERPRISE				

Source: Own elaboration based on United Nations (2002) and Narayanan and Walmsley (2008).

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)

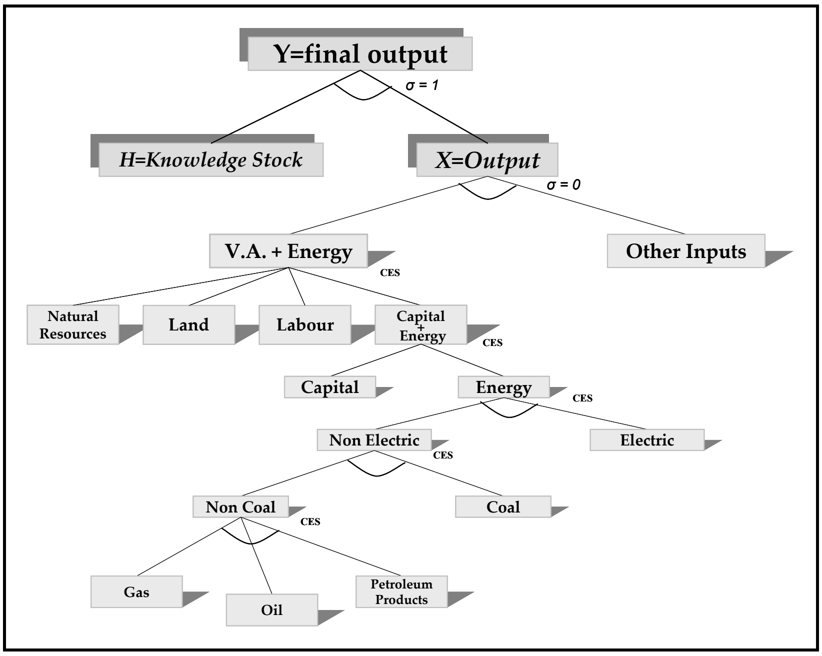
pxw	1 USA	2 EU15	3 JAPAN	4 RoA1	5 EEFSU	6 MENA	7 CHINA	8 LACA	9 RoW
1 Agriculture	0.35	0.78	0.98	0.41	-0.37	-0.97	-0.91	0.36	0.46
2 Coal	-8.42	-6.05	-7.23	-9.00	-8.03	-7.24	-12.59	-7.57	-9.10
3 Oil	-9.62	-9.28	-9.96	-9.78	-10.69	-10.63	-14.18	-9.88	-10.55
4 Gas	-4.94	-5.40	0.50	-5.45	-7.82	-6.66	16.07	-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	

CHAPTER 3: The Economy-Wide Rebound Effect and Climate Policy Effectiveness in a Multiregional General Equilibrium Framework[*]

3.1 Introduction

The insights about an increased energy consumption following efficiency improvements from technical progress, proposed initially by Jevons (1866), have significant implications on the effectiveness of energy efficiency policies. Those reflections are of particular concern for environmental and climate policy design, as revealed by the rebound effect debate summarized by Brookes (1990, 2000), Greening et al. (2000), Alcott (2005), Sorrell (2009) and Van der Bergh (2011). Moreover, the essential role of energy and its efficiency either in economic development or in climate change mitigation might have different and sometimes contradictory outcomes. On the one hand, economic development is closely related to an increasing use of energy while on the other hand, the rising demand for energy might be related to an increased use of fossil fuels or other polluting activities with negative consequences on the environment and climate. Therefore, rebound effects should be taken into account for policy design and assessment (Sorrell, 2007, and Van der Bergh, 2011).

In this context, there are two main concerns for climate policy regarding the rebound effect. First, the negative implications of the rebound effect might reduce the effectiveness of energy efficiency improvements, as shown by the empirical evidence. This could lead to disregard the promotion of efficiency and technology transfer policies related to technical progress and a more efficient use of energy. Second, curbing greenhouse gas emissions through reduced economic growth creates an obstacle in reaching a global agreement to deal with global warming. Nevertheless, appropriately considering the rebound effect in policy design could provide an opportunity to address both concerns at the same time.

The extent of how much an energy efficiency improvement might be taken back because of the Jevons' paradox, also called the Khazoom-Brookes postulate (Sorrel, 2009), has been theoretically analysed considering different functional formulations (Saunders, 2008). It has

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[*] I am grateful to Valentina Bosetti and Marzio Galeotti for useful comments and suggestions.

also been tested empirically for specific sectors using different methodologies through historical data analysis, econometric estimations, and numerical simulations, most of them highlighting the importance of rebound effects. However, providing a rebound estimate faces some challenges as described by Sorrel (2007): i) It is not possible to conduct an experiment in a real economy, ii) Performing a counterfactual analysis is also difficult since it is not possible to observe a scenario where the energy efficiency "would not have been realised", and iii) Energy efficiency improvements cannot be isolated but affect, and at the same time are influenced by, different technical, economic, and policy aspects.

Until now, most of the studies about direct rebound effects have focused on selected sectors, which mostly depend on data availability to provide empirical estimates. For policy design purposes, those estimates must be considered bearing in mind indirect and second order effects due to market interactions. This could enhance or reduce the policy effectiveness, moreover if the policy is related to a global problem such as global warming. The general equilibrium framework has proven to be a good alternative to assess those indirect and economy-wide interactions. One of the advantages of using a CGE model is that it allows providing a counterfactual scenario that is used to calculate better estimates. However, most of the studies rely on an autonomous technical change specification, which makes it difficult to tackle the endogenous aspect of induced energy efficiency. In addition, the existent CGE studies have focused on simultaneous energy efficiency improvements in the use of different kinds of energy across several productive sectors at the same time. Therefore, the corresponding rebound estimates show a compounded-aggregated effect without differentiating the particular source related to a specific energy commodity.

Although, the economy-wide rebound effect has been studied using a general equilibrium framework, there is a lack of an analysis using a multi-region CGE model including additional feedback channels through international trade and knowledge accumulation. This paper fills this gap providing insights about economy-wide rebound effects with international feedbacks. Furthermore, implementing specific policies in selected sectors and countries could provide a synergic outcome for both development and climate strategies. In light of these considerations and of the results in this paper, it is possible to identify potential rebound effects and target specific sectors. This offers an alternative to foster a more sustainable economic development while keeping in mind environmental and climate concerns.

This paper is a first attempt to contribute to the rebound effect literature adopting a general equilibrium approach enhanced with international trade flows and endogenous technical change based on a stock of knowledge. This allows accounting for technical progress and policy-induced behaviour triggered through price signals. In particular, the main contributions of the paper are: i) to provide an analysis of the economy-wide rebound effect by means of a multi-region and multi-sector dynamic recursive CGE model, ii) to estimate specific rebound effects considering single energy commodities one at a time and also for each region in the model, and iii) to offer insights about the effectiveness of both energy efficiency and climate policies at the regional level and by type of energy to select potential effective combinations for climate and development policy implementation.

The results of this paper suggest that short-run rebound effect estimates in general equilibrium are higher compared to direct rebound empirical estimations based on partial equilibrium. Regarding capital-energy substitution, lower elasticities produce also lower rebounds. In addition, the rebound effect seems to be more sensible to lower elasticities of supply for fossil fuels and inter-fuel substitution than to substitution between capital and energy. Within the majority of industries, a carbon tax policy is much more effective than energy efficiency use policies, due to a lower rebound. However there are some exceptions depending on the sector and country. This should be taken into account when designing climate and energy efficiency policies.

The paper is structured as follows: section 2 introduces a set of definitions found in the literature to select the most appropriate ones in order to estimate the economy-wide rebound. Section 3 presents a summary of the different studies found in the literature. Section 4 offers a brief description of the CGE model used along with the scenarios selected for a sensitivity analysis. Section 5 shows estimates for the short and long-run economy-wide rebound from the CGE model taking into account energy efficiency and climate policies. Section 6 concludes.

3.2 Rebound effect definitions

3.2.1 Basic rebound definition

The expected consequence following an improvement in energy efficiency should be a reduction in the use of energy. In the context of a production process, less energy to produce a given amount of output (ceteris paribus) is necessary. The rebound effect measures by how much energy efficiency improvements are offset by actual changes in energy demand. For example, if the expected potential reduction of energy demand following an energy efficiency improvement is 10 units, but actually energy demand decreases only by 9 units, then the rebound effect is equal to 10%. This overall outcome is the result of different mechanisms triggered at the same time by technology improvements, and has been classified by Greening et al. (2000)[19] and Sorrel and Dimitropoulos (2008) as:

- ***Direct rebound effects***: Related to a reduction in the cost of using/buying the more efficient product (energy services), which can lead to stimulate its demand and therefore would imply an increase in energy used to produce it (pure price effect).
- ***Indirect or secondary effects***: Associated to the lower relative cost of the product (energy services), which will change the demand for other goods and services and their corresponding energy requirements.
- ***Economy wide effects***: Considering the influence of both direct and indirect effects of the energy efficiency improvement and the interrelationship of different markets adjusting in the economy. This should be regarded as the combination (not the sum) of direct and indirect effects.

Energy efficiency (ε) is defined as the ratio between *useful work* and *energy*: $\varepsilon=S/E$. This simply represents the energy required to produce a unit of useful work. Then, an intuitive definition of the rebound effect is related to the efficiency elasticity of demand for energy also called energy conservation, $\eta_{\varepsilon}(E)$, according to Saunders (2000b), where E is energy demand and ε is energy efficiency:

$$\eta_{\varepsilon}(E)=\frac{\partial E}{\partial \varepsilon}\frac{\varepsilon}{E} \qquad (1)$$

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[19] Greening et al. (2000) mention a fourth typology described as transformational effects related to changes in consumer preferences and structure of society and productive processes, acknowledging that these effects may be difficult to identify and measure.

An elasticity equal to -1 means that the reduction of energy demand is equal to the increase in energy efficiency, therefore giving a null rebound; while if it is above -1 it denotes a positive rebound effect. There are two additional particular cases: 1) Backfire, when the energy demand increases instead of decreases, and 2) Super-conservation, when the decrease rate of energy demand is greater than the expected reduction promised by the efficiency improvement. For the purposes of this paper, a first definition of the rebound, RE_1, is given following Saunders (2000b):

$$RE_1 = 1 + \eta_\varepsilon(E) \qquad (2)$$

3.2.2 A distinction between energy and energy services

In the debate about the existence of the rebound effect and its empirical estimation there are some distinctive definitions that have arisen and are worth taking into account. Howarth (1997) considers the concept of ***energy services*** (*ES*) in a model of economic growth to distinguish it from ***energy demand*** (*E*) or physical fuel (Saunders, 2000a, 2000b). In fact, *energy services* are produced with energy in combination with other commodities. Sorrel and Dimitropoulos (2008) enhance the distinction in order to introduce ***useful work*** (*S*) which is an "...essential feature of an energy service..." that allows to be measured through physical or thermodynamic indicators. In addition, there are attributes such as comfort, speed or prestige, which can be combined with *useful work* to provide the full *energy service*.

Although taking into account useful work has its advantages because of measuring, the rebound effect definitions derived from energy services are analogous to those definitions considering useful work. This can be confirmed by comparing the rebound definition based on energy services provided by Berkhout et al. (2000).

3.2.3 Direct rebound definitions

By explicitly considering the relation between useful work and energy efficiency, Sorrel and Dimitropuolos (2008) provide several definitions for the direct rebound effect based on efficiency and price elasticities.[20] The efficiency elasticity of demand for *useful work*, $\eta_\varepsilon(S)$, is:

$$\eta_\varepsilon(S) = \frac{\partial S}{\partial \varepsilon}\frac{\varepsilon}{S} \qquad (3)$$

This has been used as common measure of rebound effect (Berkhout et al. 2000), and in fact, as demonstrated by Sorrel and Dimitropuolos (2008), it is equal to the first definition of rebound RE_1, since:

$$\eta_\varepsilon(S) = 1 + \eta_\varepsilon(E) \qquad (4)$$

In addition, the energy cost of useful work (P_S) and energy price (P_E) can be introduced in these definitions considering their price elasticities. Thus, when energy prices are exogenous, the efficiency elasticity of the demand for energy can be expressed as the negative of the energy cost elasticity of useful work minus one:

$$\eta_\varepsilon(E) = -\eta_{P_S}(S) - 1 \qquad (5)$$

Conversely, if energy efficiency is constant, the efficiency elasticity of the demand for energy is equal to the negative of the own price elasticity of energy demand minus one:

$$\eta_\varepsilon(E) = -\eta_{P_E}(E) - 1 \qquad (6)$$

Summarising, if energy prices do not depend on energy efficiency, the rebound effect can be expressed as the negative of the price elasticity for useful work $\eta_{PS}(S)$, (Berkhout et al., 2000, and Sorrel and Dimitropoulos, 2008). Symmetrically, when energy efficiency is held constant, the rebound effect can be expressed as the negative of the own price elasticity of energy demand $\eta_{PE}(E)$ (Sorrel and Dimitropoulos, 2008). This is the second definition of rebound, RE_2, employed in this paper:

$$RE_2 = -\eta_{P_S}(S) = -\eta_{P_E}(E) \qquad (7)$$

These definitions consider only a single commodity or energy service. Despite the simplifying assumptions, which are based on (prices independent of energy efficiency and exogenous energy efficiency), those elasticities are a good approximation to the rebound effect. In fact, there is a close relationship with the price elasticity, since high rebounds are also a consequence of high price elasticities (Berkhout et al., 2000).

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[20] For a complete derivation of these elasticities and the different definitions of direct rebound, see Sorrel and Dimitropoulos (2008), Annex B.

3.2.4 Rebound definitions in the general equilibrium framework

Most of the research on the rebound effect is based upon empirical estimations using the direct rebound definitions that are close to a partial equilibrium framework. The remaining types of rebound (indirect and economy-wide) are more difficult to estimate given the interrelationship with other sectors and throughout the whole economy. However, there are also studies that make use of the general equilibrium theory to estimate it with numerical simulations (Semboja, 1994; Dufournaud et al., 1994; Grepperud and Rasmussen, 2004; Vikström, 2008; Allan et al., 2007; Anson and Turner, 2009; Turner, 2009; Guerra and Sancho, 2010; Turner and Hanley, 2011) and also recently providing definitions based on general equilibrium conditions (Wei, 2010 and Guerra and Sancho, 2010). Both types of approaches have their advantages and caveats. For instance, on the one hand, while theoretical definitions provide a more rigorous analysis, they depend upon the basic assumptions and formulations for production functions and upon the complexity (or simplicity) of the model. On the other hand, numerical simulations tend to bridge a gap between theory and available data providing results that allow a better understanding of the phenomenon along with the intrinsic data.

The most direct way of measuring the rebound effect within a CGE model is that of applying an exogenous shock to simulate costless improvements in energy efficiency and then check the variations in energy demand and other aggregate variables. The rebound effect should then be computed by applying the first definition from equation 2. This is commonly applied in a static model where the counterfactual scenario is the state of the economy before the energy improvement. In addition, some studies consider a baseline scenario as counterfactual estimating the rebound effect as the result of deviations from that baseline after the introduction of an energy efficiency improvement. In this case, there is the risk of including additional effects or distortions embedded in the baseline construction. Therefore, careful attention should be paid to ensure that those distortions do not bias the rebound effect estimate.

On the theoretical side, Wei (2010) provides an analysis considering a general equilibrium framework within the perspective of a simplified model of a global economy. The study offers useful insights through definitions of the rebound effect both in the short and long-run, highlighting the determinant role of supply in the final rebound outcome. Wei's paper contributes by considering general equilibrium conditions and, particularly, it concludes that substitution between energy and other factors is more relevant for the long-term analysis when capital becomes endogenous. Nevertheless, the model formulation does not acknowledge an explicit substitution relationship between capital and energy, a fact that may also influence the final rebound effect (Sorrel, 2008). Another limitation acknowledged in the study is that the consideration of a global economy, disregards possible effects due to the international and intersectoral trade inherent to the economy.

A recent paper expresses the concern that the general equilibrium evaluation of the rebound effect might be biased given that the changes in the energy efficiency introduced in the simulations, which come from engineering estimations, are related to a partial equilibrium framework (Guerra and Sancho, 2010). The logic of the argument lies in the fact that the changes in energy demand in equation 1 are Actual Energy Savings (AES), which are compared with the Potential Energy Savings (PES) represented by the change in energy efficiency, so rewriting equation 2:[21]

$$RE_1 = 1 + \eta_\varepsilon(E) = 1 + \frac{\frac{\partial E}{E}}{\frac{\partial \varepsilon}{\varepsilon}} = 1 - \frac{AES}{PES} \qquad (8)$$

To correct the mentioned bias, the authors propose to use a measure for the potential savings that should also be computed according to a general equilibrium framework but where the price effects are omitted deactivating any rebound mechanism. For that purpose they make use of the Input-Output framework to calculate the corresponding potential energy savings, offering an unbiased measure of the rebound effect in the general equilibrium framework. The main insight of this new measure is that using potential energy savings from a partial equilibrium framework biases the economy wide rebound downward and upward biases backfire. These concerns indicate the risk of underestimating the rebound effect, and the study suggests an interesting procedure to solve the problem. However, the fact remains that the new potential energy savings rely more on an input-output analysis than on a general equilibrium framework.

An alternative measure of the economy-wide rebound effect could be evaluating the changes in the energy intensity of GDP as energy efficiency improvements. In this case, a decrease of

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[21] The change of sign in the formula is explained because both AES and PES now refer to energy savings and have the same sign, therefore, if AES=PES the rebound effect is null. This is clearly the opposite case compared to the previous definitions that confront an increase in energy efficiency with a decrease in energy demand.

the energy intensity measured by the physical units per GDP is taken as a wide-energy efficiency improvement that is the outcome of the exogenous energy efficiency based on engineering estimations. This would offer a wide measure calculating the aggregated regional rebound effect. However, Saunders (2000a) expresses some concerns about using energy/GDP ratios because this ratio depends upon the behaviour of energy prices and this may mask the final effect. Notwithstanding this argument, when considering the wide-economy rebound effect in a general equilibrium framework, the role of prices is an important component of the wide measure. This is a fact which is also supported by the influence of the price elasticity of demand for energy, used as a measure of direct rebound as explained above.

3.3 The rebound effect in the literature

There are several studies that estimate and measure the rebound effect considering different approaches and techniques. Most of them focus on specific sectors relying either on historical data or on available survey data. For instance, Schipper and Grubb (2000) provide a general analysis using historical data on energy intensity for developed countries and for particular sectors in response to energy efficiency improvements, without using formal statistical or modelling methodologies, concluding that rebound values are low, considering observed energy prices and costs.

The empirical literature has focused on direct rebound with estimations mostly for household energy services in developed countries as Sorrel et al. (2009) point out in a review of the literature from 1979 to 2008. By analysing and classifying those studies according to the estimation methodology and approach, the authors suggest ranges for the direct rebound effect as best guesses for selected energy services (Personal automotive transport and Space heating: 10%-30%, Space cooling: 1%-26%, Other consumer energy services: less than 20%).

At the macroeconomic level, Barker et al. (2009) estimate a macroeconomic rebound effect of around 50% for 2030 as the result of simulating energy efficiency policies. The model used is E3MG, which is a dynamic macro econometric model, with exogenous estimations for energy savings based mostly on the World Energy Outlook 2006 (IEA 2006). The paper proposes a definition of the macroeconomic rebound effect as the combination of indirect and economy-wide effects, and calculates it as the difference between a total rebound effect and the direct rebound. For the final calculation the paper relies on direct rebound estimations taken from the literature (see Sorrell, 2007, and Sorrell et al., 2009). In a previous study using a similar methodology Barker et al., (2007) examine the macroeconomic rebound effect for the UK derived from energy efficiency policies in 2000-2010, finding a range from 5% to 30%.

Dimitropuolos (2007) provides a review of conclusions coming from different areas of research, which focused on the macroeconomic level considering growth models and related empirical estimations as well as CGE models. Regarding neoclassical growth models, the debate developed around the analysis and conclusions from Saunders (2000a, 2000b) and Howarth (1997). The insights from growth models were evaluated by empirical econometric evidence, but focused more on technical change than specifically on the rebound effects. CGE studies provide additional and more detailed information to understand the economy-wide rebound effects, however their results depend on the model's structure and on critical parameter values. Semboja (1994) analyses the implications of energy efficiency improvements in Kenya and concludes that the rebound effect might be higher than 100%. Dufournaud et al. (1994) use a CGE model for Sudan to study the effects of introducing improved wood burning stoves, which yielded a rebound effect between 47% and 77%. The main findings of all the studies covered in the paper are summarised in Table 1, taken from Dimitropuolos (2007), which has been extended with recent studies.

Table 1: Summary of results from CGE studies

Study	**Country**	**Production Functions***	**Elasticities of substitution**	**Rebound effect %**
Semboja (1994)	Kenya	CD, L	1	170-350
Dufornaud et al. (1994)	Sudan	CES	0.2-0.4	47-77
Van ES et al. (1998)	Holland	CES	0<σ<1	15
Vikström (2008)	Sweden	CES	0.07-0.087	60
Grepperud and Rasmussen (2004)	Norway	CES	0<σ<1	<100
Washida (2004)	Japan	CES	0.3-0.7	35-70
Glomsrod and Wei (2005)	China	CD, L, CES	1	>100
Hanley et al. (2005)	Scotland	CES	0.3	120
Allan et al. (2007)	UK	CES	0.3	30-50
Turner (2009)	UK	CES	0.3	-45-59
Anson and Turner (2009)	Scotland	CES,L,CD	0.3-5	34-41
Guerra and Sancho (2010)	Spain	CES	≈0-1.5	14-230
Turner and Hanley (2011)	Scotland	CES,L,CD	0.4-1.1	60->300

Source: Dimitropuolos (2007),

* CD: Cobb-Douglas, L: Leontief, CES: Constant elasticity of substitution

Grepperud and Rasmussen (2004), use a CGE model applied to Norway to explore the rebound effect of energy improvements in various sectors regarding the use of electricity and oil. The study compares a baseline scenario until 2050 with an alternative one where energy efficiency improvements have been introduced separately in manufacturing and finance sectors for electricity use; and in road transport and fisheries sectors for oil use. Rebound estimates are then calculated as the difference with respect to the baseline scenario being less than 100% with significant effects for industries.

A particular CGE study is that of Vikström (2008) who performs a counterfactual comparison with historical data for the Swedish economy in 1957, for a period of 5 years until 1962. The counterfactual has been built based on estimates of historical changes in energy efficiency and the rebound effect is found to be 60%. One of the contributions of the paper is the attempt to link the rebound effect to the environmental Kuznets curve where the rebound effect plays an important role related to technical progress. Following the same line of research, Turner and Hanley (2011) analyse the relation of the environmental Kuznets curve and rebound through technical change with a CGE model for Scotland. By introducing a 5% increase in energy efficiency in all production sectors, and with different elasticities of substitution, the authors find a high rebound effect in the short-run, and backfire in the long-run. Allan et al. (2007) use a similar CGE model for the UK providing a sensitivity analysis based on different scenarios considering not only ranges for elasticities of substitution, but also the impact of recycling government revenues and a costly implementation of the energy efficiency imposed. Estimates of the rebound are above 50% for the short-run and 30% for the long-run. Further studies with similar models consider disinvestment effects related to rebound effects for the UK with estimates around 45% and 59% (Turner, 2009) and for the oil sector in the Scottish transport sector ranging between 34% to 41% (Anson and Turner, 2009).

All of the studies based on CGE models have focused on single countries and on specific sectors, but there are also recent contributions both to the definition of rebound effect and to the theoretical analysis in the general equilibrium framework. Wei (2010) provides a theoretical consideration over a small, simplified general equilibrium framework, offering insights for the short and long-run considering conditions for rebound, backfire and super-conservation. Regarding the rebound definitions, specifically in general equilibrium, Guerra and Sancho (2010) propose an unbiased measure of the economy wide effect by combining the input-output analysis with the general equilibrium framework, to compute the energy savings in the general equilibrium framework corresponding to the potential energy savings suggested by engineering estimations. By imposing a 5% improvement in energy efficiency in a CGE model for Spain, they found an unbiased economy-wide rebound of 91% compared to a biased rebound of 87%, computed following common rebound definitions.

3.4 CGE modelling framework

We set out to study rebound effects by means of a CGE model. The main reason is that this framework can provide a counterfactual as a valid reference scenario for further comparisons. Moreover, one advantage of a CGE analysis is that it allows studying the rebound effect through a series of experiments taking into account energy efficiency improvements which can be exogenous or also induced by specific policies. Another advantage relies on the possibility to check the robustness of the results through a sensitivity analysis.

3.4.1 The ICES model

This study relies on a recursive-dynamic CGE model of the world economy, ICES, in which different regions interact with each other through several channels: prices, capital, and trade flows. Although the main common limitation of most large-scale CGE models is the lack of an endogenous evolution of technical change, the special characteristics that render ICES valuable for this exercise refer to the explicit formulation of technical change present both in an endogenous and exogenous way. For the first behaviour, this particular version has been enhanced to include endogenous technical change trough the use of a stock of knowledge and investments on research and development (R&D). For the second behaviour, and as a result of the core formulation of the model, it is possible to impose exogenously additional technical change improvements through a set of technology parameters allowing to distinguish factor-use improvements at different levels of the production structure.

The core of the model is summarised in the following equations.[22] Final output in sector (Y_i) is produced by combining the stock of knowledge (H_i) with a composite X_i, which is the output obtained by combining value added (VAE) and other intermediate inputs M. The parameter ρ is related to the elasticity of substitution σ: $\rho=(\sigma-1)/\sigma$. Value added is produced using production factors (labour Lb and land Ln) and a capital energy composite (KE). The KE composite is obtained by combining physical capital K with energy commodities E.

$$Y_i = \overline{H}_i \cdot \left[\alpha_i \cdot H_i^{\rho} + (1-\alpha_i) \cdot X_i^{\rho}\right]^{\frac{1}{\rho}} \tag{5}$$

$$X_i = f(VAE_i, M_i) \tag{6}$$

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[22] The detailed description of modifications to include endogenous technical change and the stock of knowledge in the model and database is described in chapter 2.

$$VAE_i = f(Lb_i, Ln_i, KE_i) \tag{7}$$

$$KE_i = f(K, \varepsilon \cdot E) \tag{8}$$

$$\overline{H}_i = H_i^{\gamma_i} \tag{9}$$

The technology externality $\overline{H}_i$ in sector *i* represents the increase in production that benefits firms due to intrasectoral spillovers from sector specific knowledge capital. The stock of knowledge H_i directly benefits firms while the indirect effect of $\overline{H}_i$ is regulated by the parameter $\gamma_i>0$, which denotes the elasticity of R&D services to total factor productivity in every industry.

As for technical change improvements, endogenous technical change is governed trough investments in R&D that accumulate in a knowledge stock, while exogenous shocks can be imposed for every factor and intermediate commodity in the productive process. Equation 8 highlights this possibility by explicitly including the energy augmenting parameter ε that represents costless improvements in energy efficiency that allow for a lower energy use. The regional aggregation of the model along with the sector in every economy is detailed in table 2.

Table 2: Regions and sector in the ICES model

Regions		***Sectors***	
USA	United States of America	*Agriculture*	Agriculture
EU15	European Union 15	*Coal*	Coal
JAPAN	Japan	*Oil*	Oil
RoA1	Rest of Annex 1 countries	*Gas*	Gas
EEFSU	Easter Europe and Former Soviet Union	*Oil_Pcts*	Oil products
MENA	Middle East and North Africa	*Electricity*	Electricity
CHINA	China	*En_Int_ind*	Energy Intensive Industries
LACA	Latin America and the Caribbean	*Oth_ind*	Other manufacturing industries
RoW	Rest of the world		

3.4.2 Sensitivity analysis

An important matter in applied CGE modelling is the robustness of the analysis. CGE models results depend not only on the data they use, but also on the underlying parameters specified in the model's formulation. Among these, the elasticities of substitution are crucial to determine the model's behaviour. Moreover, one of the key factors for the analysis of the rebound effect is the substitution between capital and energy ($\boldsymbol{\sigma_{KE}}$) (Sorrel, 2008). In order to provide robust results and a reliable assessment of the rebound effect with the CGE model, all simulations have taken into account a sensitivity analysis based on this parameter. The following scenarios with their correspondent values for $\boldsymbol{\sigma_{KE}}$ have been chosen for the sensitivity analysis:

1) **σ_{KE} = *0.5:*** Elasticity of substitution between capital and energy σ_{KE} equal to 0.5 as in the original formulation of the CGE model.
2) **σ_{KE} = *0.25:*** Elasticity of substitution between capital and energy σ_{KE} equal to 0.25 in accordance to recent estimations that suggest a lower value for this parameter (Okagawa and Ban, 2008; Carraro and De Cian, 2009; and Beckman et al. 2011).
3) **σ_{KE} = *0.25*:*** Elasticity of substitution between capital and energy σ_{KE} equal to 0.25, and a new set of values for elasticities of supply of fossil fuels and for energy substitution. The motivation for using these values follows Beckman et al. (2011), who test the ability of the GTAP-E model (Burniaux and Truong, 2002), to replicate the historical volatility of the world petroleum market. The proposed set of values offers a more realistic behaviour of the global petroleum products consumption along with a price inelastic demand. Regarding the elasticities of supply: i) coal is set to 1 instead of the range [0.5-0.61], ii) oil is equal to 0.25 instead of [0.5-0.63], and iii) gas is set to 0.6 instead of [1-18]. In addition, energy substitution elasticities have lower values: i) 0.16 between electricity and non-electricity, ii) 0.07 for coal, and non-coal, and iii) 0.25 between oil products. This last set of values are more valid according to the recent studies that support both a lower value for σ_{KE} and the new set of elasticities, since they seem to better replicate some features of fossil fuel markets (Beckman et al., 2011).

The next section presents all results taking into account these three scenarios for the sensitivity analysis to understand if different values of the σ_{KE} parameter produce different rebounds.

3.5 Rebound effect insights from general equilibrium

The following analysis applies some of the rebound effect definitions from section 2 in the general equilibrium framework described in the previous section. It first focuses on general equilibrium elasticities to provide a first insight of possible rebound values. Then the improvements of energy efficiency are analysed taking into account not only short and long-run estimates for single energy commodities, but also considering an economy wide rebound effect. Finally it explores some policy implications keeping in mind the energy efficiency use induced by climate policy. All efficiency improvements have been introduced only in productive sectors and not in final private or public consumption.

3.5.1 General equilibrium own price elasticity of demand

A first approximation to the rebound effect can be through general equilibrium elasticities of demand, given that the new equilibrium depends upon the value of those elasticities. As Hertel et al. (1997) point out: "...the GE own-price elasticity of demand for a given product is critical for determining the distribution of benefits from technical change in an industry...". These GE elasticities are shown for energy commodities in table 3 for distinct values of the elasticity of substitution between capital and energy. They have been computed by applying a shock to the model to increase the price of each commodity in each region one at a time and then calculating the variation of the output with respect to its own price. A first conclusion related to the influence of the capital-energy substitution elasticity (**σ_{KE}**) is that when it is halved the price elasticity values are very similar. There is a difference only when the new values for the supply elasticities of fossil fuels and energy substitution elasticities are considered, reducing the potential rebound effect in almost all cases.

Table 3: General equilibrium price elasticity of energy commodities

Energy	**Coal**			**Oil**			**Gas**			**Oil Products**			**Electricity**		
σ_{KE}	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****
USA	-0.76	-0.71	-0.41	-1.97	-1.94	-1.62	-0.94	-0.90	-0.54	-1.10	-1.03	-0.84	-0.85	-0.78	-0.43
EU15	-1.65	-1.62	-1.37	-3.29	-3.25	-2.82	-1.98	-1.97	-1.66	-1.41	-1.31	-1.14	-0.93	-0.86	-0.50
JAPAN	-2.62	-2.62	-2.61	-2.54	-2.54	-2.53	-1.73	-1.73	-1.72	-1.10	-1.03	-0.77	-0.77	-0.66	-0.39
RoA1	-2.50	-2.48	-1.97	-3.07	-3.00	-2.29	-2.02	-2.01	-1.59	-1.51	-1.43	-1.24	-1.12	-1.05	-0.73
EEFSU	-1.14	-1.13	-0.82	-1.84	-1.77	-1.23	-0.98	-0.92	-0.58	-1.41	-1.34	-1.07	-0.86	-0.79	-0.50
MENA	-2.00	-1.99	-1.83	-1.45	-1.35	-0.78	-1.33	-1.29	-0.95	-1.62	-1.53	-1.41	-0.75	-0.69	-0.31
CHINA	-0.85	-0.78	-0.54	-1.93	-1.90	-1.66	-1.23	-1.23	-0.89	-1.13	-1.05	-0.81	-0.81	-0.71	-0.32
LACA	-3.13	-3.13	-2.86	-2.11	-2.04	-1.50	-1.15	-1.12	-0.76	-1.20	-1.11	-0.93	-0.84	-0.76	-0.41
RoW	-1.84	-1.82	-1.34	-2.89	-2.80	-1.93	-1.39	-1.36	-0.93	-1.15	-1.05	-0.86	-0.82	-0.74	-0.32

Although this elasticity constitutes a direct measure of the rebound effect in a partial equilibrium analysis, it is not possible to say the same in this particular case given that in a CGE model prices are endogenous and the values of the GE elasticities reflect the adjustments in all markets. Furthermore, in order to obtain a real measure of the rebound effect they should be adjusted taking into account the supply elasticities as suggested by Wei (2010) and also considering capital-energy substitution (Saunders, 2008 and Sorrel, 2008). This first exercise though, is a good approximation of the potential rebound and also useful to identify the regions and energy commodities that are prone to show a higher rebound. For instance, in the last case where the set of parameters are calibrated to better reproduce the behaviour of petroleum markets (***σ_{KE}=0.25****), oil has the higher absolute values for the price elasticity of demand for most regions except for Japan, MENA and LACA. However, coal has a higher elasticity in those regions.

It must be carefully regarded that although in the model oil is considered an energy commodity, it is mainly used as a feedstock, which becomes the main input to produce oil products. This is important when accounting for CO_2 emissions given that when oil is transformed in oil products it is not used as conventional energy but refined, and that process does not produce emissions as in the case oil were just burned. This issue must be kept in mind when evaluating the rebound effect in the following analysis. In fact, as it is one of the main inputs for producing oil products, there is a reinforcement effect since a decrease in the price of oil reduces even more the cost of oil products. This increases the demand and production of oil products, explaining the high rebound effect for oil. Referring to the GE values, and disregarding the case of oil for a moment, the energy commodities with values below -1 could present higher rebounds, particularly in coal, gas and oil products.

3.5.2 Energy efficiency improvements

3.5.2.1 Short-run rebound

To estimate the effects on the short-term, the selected method used for assessing the economy-wide effect through the CGE model is by applying an exogenous shock to energy augmenting productivity to simulate an increase of 1% in energy efficiency for the five energy commodities in the database. This is the only shock imposed to the model in order to obtain an estimate of the short-run rebound effect for each type of energy. The assumed increase in energy efficiency is then compared with the corresponding change for the same energy commodity demand.

To understand if the change in efficiency is further influenced through international trade flows, the corresponding rebound has been computed first by applying the increase in energy efficiency for a single commodity in all regions at the same time and then by one region and commodity at a time. Table 4 shows the rebound for the first case in which the energy efficiency shock has been applied to all regions at the same time. The lower rebound is for coal in all regions, particularly in LACA (9%). Higher rebounds are found for oil products in developed regions (USA, EU15, JAPAN and RoA1) and electricity. As in the case of price elasticities, rebound is not very sensitive to changes in σ_{KE}, but show a lower value for the case $\sigma_{KE}=0.25*$, suggesting that it could be in the ranges of 9-36% for coal, 43-80% for oil, 36-84% for gas, 41-94% for oil products, and 35-57% for electricity. Similar to the case of GE elasticities, the lower the substitutability between energy and capital, the lower the rebound effect. The rationale of this outcome is the following. In a first stage, the energy efficiency reduces energy demand and then the energy price diminishes. Since energy has become cheaper, its demand should increase generating a rebound effect. Furthermore, if the capital-energy substitution elasticity is higher, then capital will be substituted with cheaper energy increasing the rebound even more. Therefore, only when there is a low possibility to substitute capital the rebound will be lower. A similar situation occurs when inter-fuel substitution in general is reduced, as in the case of $\sigma_{KE}=0.25^*$, and the rebound effect is found to be less. The lower elasticities of inter-fuel substitution reflect a more rigid production process where a cheaper energy commodity cannot easily substitute other energy goods.

Table 4: Rebound effect by energy commodity for all regions at the same time (in percentage)

Energy	**Coal**			**Oil**			**Gas**			**Oil Products**			**Electricity**		
σ_{KE}	*0.5*	*0.25*	*0.25**	*0.5*	*0.25*	*0.25**	*0.5*	*0.25*	*0.25**	*0.5*	*0.25*	*0.25**	*0.5*	*0.25*	*0.25**
USA	52	47	26	76	71	75	77	73	57	92	86	83	89	81	49
EU15	51	47	23	80	73	80	95	93	84	102	93	94	90	82	50
JAPAN	37	34	13	77	72	68	90	85	54	97	92	81	82	71	46
RoA1	56	50	23	69	62	61	63	60	38	90	83	77	87	79	48
EEFSU	48	46	23	72	66	55	85	78	63	88	81	59	91	82	57
MENA	51	51	19	66	59	56	65	61	50	89	80	77	95	89	50
CHINA	54	45	36	61	53	43	89	89	39	75	65	41	84	72	35
LACA	36	36	9	60	52	51	68	65	36	87	78	74	88	80	46
RoW	52	49	21	74	65	66	76	72	43	89	79	73	92	83	42

Table 5 shows results if instead of applying the efficiency improvement to all regions at the same time it is done one region and energy commodity at a time. Again, rebound values are only slightly different when σ_{KE} is equal to *0.5* or *0.25*. A different situation shows for the case $\sigma_{KE}=0.25^*$, where rebound is definitely lower. The range of the rebound remains in the same magnitude within ranges of 8-33% for coal, 64-101% for oil, 33-63% for gas, 30-67% for oil products, and 37-59% for electricity; suggesting a possible backfire for oil only in the Middle East and North Africa (MENA) region.

The influence of international trade on the rebound effect becomes evident when comparing tables 4 and 5, when the efficiency improvement is realised in an isolated way on a single region only. The main propagation channel is the international price of the energy commodity. If the change in price in one commodity is widely diffused across the world, the rebound effect should be expected to be higher. This should be the case when the energy efficiency improvement has been applied in all regions (table 4). In particular, this verifies for coal, oil products, and gas; since rebounds are lower when the energy efficiency improvements are only within a single region and commodity. Conversely, whilst oil presents higher rebound effects for all regions but USA and JAPAN, electricity rebound is only slightly higher when the efficiency improvement is in one region at a time.

Table 5: Rebound effect for energy commodity by region and energy sector one at a time (in percentage)

Energy	**Coal**			**Oil**			**Gas**			**Oil Products**			**Electricity**		
σ_{KE}	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****	***0.5***	***0.25***	***0.25****
USA	52	47	24	90	85	74	77	73	53	88	80	58	90	83	50
EU15	50	46	20	111	104	93	91	89	63	100	89	67	92	85	51
JAPAN	35	32	10	87	81	62	83	79	36	93	84	51	83	73	47
RoA1	54	48	18	107	102	90	66	63	32	86	76	50	90	83	50
EEFSU	48	47	21	107	102	86	86	79	59	88	79	44	93	85	59
MENA	49	49	16	117	111	101	66	62	42	85	73	54	95	89	51
CHINA	54	45	33	85	79	64	87	87	36	75	63	30	86	76	37
LACA	35	35	8	91	85	74	70	67	33	85	74	56	90	82	48
RoW	51	47	18	97	89	77	76	73	36	87	75	53	94	86	44

The low overall export ratio over total output of electricity is the main reason why its rebound is very similar in both cases.[23] In fact, according to the data, these ratios are less than 5% suggesting a low influence on the electricity world price following energy efficiency improvements, and thus a very low effect of international trade. Differences for coal are also small and although its trade is higher internationally, it is not present in all regions. Therefore the higher rebound differences are mostly found in regions with an important coal export share over total output (RoA1, EFFSU and RoW).

The widespread international trade of oil, gas and oil products, provide a fluid channel to affect world prices, and moreover, they belong to an inelastic world market as determined by their low elasticities of supply. This would explain the higher differences between tables 4 and 5. The lower rebound values when the efficiency use improvements are isolated are explained by the relative importance of international trade of oil products and gas, with a share of world exports over world output of 14 and 27% respectively.

To conclude the analysis of the short-term rebound, the following results consider the economy-wide effect in terms of energy intensity of GDP as explained in the last paragraph of section 3.2.4. In this case, the changes in energy intensity take into account changes in energy use in quantities (toe) and in real GDP disregarding changes in nominal prices since the

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[23] The reason for a higher rebound when the efficiency improvement is applied in only one region may be due to a low elasticity of substitution among electricity and non-electricity as modelled in ICES. A further sensitivity analysis could provide an answer for this issue but it is not the scope of this paper.

model can decompose the growth of GDP in terms of values and quantities. This consideration provides a better estimation of the regional wide rebound effect and at the same time includes the concerns expressed by Saunders (2008a) about using energy/GDP ratios when evaluating it. The following results take into account only the third sensitivity scenario ($\sigma_{KE}=0.25*$), which is regarded to represent the more valid set of parameters for the model.

Table 6 shows the regional-wide effect when the energy efficiency is applied to each energy commodity for all regions at the same time. The overall effect is reduced when the entire economy and not only the energy sector is taken into account. The rebound effect is dissipated throughout all markets with a diluted effect on GDP and total energy use. Again, for the case $\sigma_{KE}=0.25*$, the energy sectors that have a greater influence on the regional-wide rebound are gas (3-46%), oil products (13-87%) and electricity (10-33%), with the higher value corresponding to oil products in the Rest of the World (RoW). Coal is less than 9% while oil shows a negative rebound between -52% and -6%.

Table 6: Regional-wide rebound effect for total energy (in percentage)

Region	Coal	Oil	Gas	Oil Products	Electricity
USA	2	-7	20	36	10
EU15	1	-11	4	29	11
JAPAN	1	-6	3	13	14
RoA1	1	-11	5	16	12
EEFSU	9	-52	46	63	33
MENA	4	-25	21	53	20
CHINA	8	-21	3	56	18
LACA	2	-18	8	24	21
RoW	3	-23	16	87	16

Note: Results corresponding to the third scenario ($\sigma_{KE}=0.25*$)

These results reveal interesting insights about the possible effectiveness of energy efficiency and climate policies at the regional level when the efficiency improvement starts only in one sector. For instance in the case that an energy efficiency improvement is implemented throughout the world in the use of oil products, that particular policy would be more effective in JAPAN and RoA1 with lower regional-wide rebound effects (13% and 16% respectively). The policy effectiveness would be weakened by the regional-wide rebound in most developing countries as well as in USA and EU15.

While the previous analysis is useful for identifying the regions with lower potential for energy efficiency improvements, table 7 shows the effects on the regional-wide rebound when the energy efficiency improvement occurs only in one region at a time for a specific energy commodity. Therefore, selecting and targeting a better policy for each region is possible.

Comparing values from the previous example for oil products, the regional-wide rebound effect is lower for all regions. The comparison provides additional information to select the regions where energy efficiency policies would be more effective. Once more, developed regions would show a lower rebound for efficiency improvements in the use of oil products while developing regions still have higher rebound values which could translate into not only additional liquid fuel consumption, but also into higher CO_2 emissions compared to the expected reductions with the policy.

Table 7: Regional-wide rebound effect for total energy by region and sector one at a time (in percentage)

Energy	Coal	Oil	Gas	Oil Products	Electricity
USA	2	-11	18	13	11
EU15	3	-12	5	15	15
JAPAN	2	-8	4	6	16
RoA1	2	-13	5	11	15
EEFSU	9	-72	45	55	37
MENA	8	-35	16	29	23
CHINA	8	-27	11	39	19
LACA	4	-28	9	17	26
RoW	3	-35	18	35	18

Note: results corresponding to the third scenario ($\sigma_{KE}=0.25*$)

Another interesting example regards electricity. Developed regions show a lower regional-wide rebound effect with much higher values for developing regions. This could represent a potential advantage given that the demand corresponding to the electricity rebound could be produced with renewable or cleaner energy. This could foster growth in those regions with a corresponding demand supported by the expansion of renewable energy industries, which could help to change the energy supply matrix of the country.

3.5.2.2 Long-run rebound

In the long-term, capital is mobile and therefore influences the value of the rebound effect. According to Saunders (2008) the long-run rebound should be higher than the short-run due to a greater output and thus a higher overall demand. From the theoretical analysis Wei (2010) suggests that there is the possibility of a higher short-run rebound under certain conditions such as a large own price elasticity of supply, although this does not seem to be the case. The evidence from the long-run rebound effect gives different values for some sectors. When compared with the short-run, there is no agreement if its value should be below or above.

Various empirical studies about direct rebound estimates reviewed by Sorrell et al. (2009) found the long-run rebound to be higher. Conversely, CGE studies from Allan et al. (2007)

and Turner (2009) find that short-run rebound is higher for the UK when all production sectors increase their energy efficiency by 5%. The argument supporting a higher short-run rebound has been referred to as the disinvestment effect, which dampens rebound in the long-run (Turner, 2009). This would be the outcome of a reduced profitability due to falling prices that lead to a contraction of capital stock on energy sectors. Moreover, that reduction of profitability would occur when the general equilibrium price elasticity of energy demand is inelastic. Nevertheless, in a similar study for the Scottish refined oil sector, the disinvestment registered is not enough to produce a lower long-run rebound effect (Anson and Turner, 2009).

The long-run estimate has been computed by means of a baseline built with the dynamic-recursive model in order to allow for capital accumulation and therefore a growing economy. Once the baseline is ready, the rebound effect can be estimated following the same procedure as in the short-run, just by imposing an additional shock to increase energy efficiency by 1% to the baseline scenario. The differences between the efficiency scenario and the baseline simulation provide the long-run estimates. These are shown for 2010 and 2050 in table 8 along with their corresponding short-run values. Again, all estimates relate to the third sensitivity scenario σ_{KE}=*0.25**.

Table 8: Long-run rebound effect by energy commodity for all regions at the same time (in percentage)

Region	**Coal**			**Oil**			**Gas**			**Oil Products**			**Electricity**		
	Short run	***Long run***		***Short run***	***Long run***		***Short run***	***Long run***		***Short run***	***Long run***		***Short run***	***Long run***	
		2010	***2050***		***2010***	***2050***		***2010***	***2050***		***2010***	***2050***		***2010***	***2050***
USA	26	29	45	75	86	82	57	64	82	83	89	78	49	43	43
EU15	23	24	33	80	93	89	84	88	90	94	102	89	50	40	43
JAPAN	13	12	15	68	77	56	54	58	68	81	87	55	46	37	39
RoA1	23	24	34	61	70	68	38	45	67	77	82	69	48	42	42
EEFSU	23	24	31	55	72	91	63	74	97	59	76	95	57	68	69
MENA	19	19	26	56	68	81	50	60	83	77	87	99	50	60	57
CHINA	36	43	68	43	62	81	39	39	46	41	62	85	35	49	44
LACA	9	7	6	51	63	83	36	43	65	74	84	91	46	43	46
RoW	21	22	21	66	88	135	43	49	65	73	95	143	42	40	44

For most cases the long-run rebound is higher, in accordance to Saunders (2008) and Wei (2010), with some exceptions (coal in LACA, and electricity in USA, EU15, Japan and Rest of Annex 1). In fact, there is a reduction of capital stock in all energy sectors but oil products in the rest of the world, which supports the disinvestment effect proposed by Turner (2009). However, the higher short-run rebound is present only in some cases, and it is not always where the absolute value of the general equilibrium price elasticity is less than 1, as for example in the case of electricity for EEFSU, MENA and CHINA (see table 3, last column).

The information in table 8 provides additional elements to take into account for policy design. For instance, even though there is a considerable rebound for electricity in all regions, an energy efficiency policy would be less effective in developing countries such as EEFSU and MENA both in the short and long-run. Although there seems to be a higher rebound in developing countries that increases with time when capital is allowed to change, this fact should not be considered as a negative element for the policy effectiveness from the climate change point of view. On the contrary, it should be regarded as an opportunity given that the expected growth related to a higher rebound in those countries could be supplied with clean sources of energy. This could constitute an incentive for clean and renewable technology transfers in the electricity sector.

3.5.3 Rebound effects and climate policy

3.5.3.1 Climate policy rebounds: when and where to be concerned. Does energy source and technology matter?

Mitigation of greenhouse gas emissions can be achieved through many strategies and among them there are two kinds of policies that are closely related to energy consumption and the rebound effect: i) energy efficiency, and ii) a carbon price/tax on emissions. While the link between rebound and the first one has been explained above; imposing a price on carbon seeks to reduce emissions by inducing an efficient use of energy with a bias for less polluting or clean energy. This opens the chance for the existence of some rebound that could reduce the policy effectiveness.

It is possible to compare the effectiveness of both kinds of policy and also to evaluate the rebound in both alternatives by using the concept of sectoral output's energy intensity. This constitutes a good proxy to estimate changes in energy efficiency, and therefore, the rebound effect in comparable terms. For this purpose the changes in energy efficiency for every sector of the model have been computed as the ratio between variations of each type of energy used over its output. Table 9 shows the short-run estimates for an energy efficiency improvement of 1% and a carbon tax of 50US$ per tonne of carbon[24] for the following sectors: Electricity, Energy intensive industries, and Other industries.

Table 9: Short-run rebound effect for energy efficiency and carbon tax policies in selected sectors (in percentage)

Region	USA		EU15		JAPAN		RoA1		EEFSU		MENA		CHINA		LACA		RoW	
Policy	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**
Electricity																		
Coal	10	-49	3	-6	2	-17	3	-22	2	-58	0	-75	23	-102	-1	-11	5	-37
Gas	14	-76	4	-8	5	-26	3	-28	35	-90	33	-92	-	-	13	-12	10	-59
Oil_Pcts	-	-	-	-	23	-41	-	-	31	-138	49	-386	-	-	46	-31	41	-93
Energy Intensive Industries																		
Gas	4	-6	-7	56	-	-	7	19	34	-61	53	-19	-	-	6	7	3	-27
Oil_Pcts	-7	-8	1	470	6	34	-17	50	23	-108	138	-45	7	-58	11	27	29	-54
Electricity	-	-	-3	150	4	44	11	42	31	-94			9	-53	8	28	5	-40
Other Industries																		
Gas	1	-1	1	-4	-	-	1	1	3	0	2	9	-	-	1	-1	-	-
Oil_Pcts	3	-2	4	-333	2	-8	6	5	13	-1	19	22	8	-5	8	-5	10	-1
Electricity	2	-1	2	-15	2	-10	2	4	6	-1	3	20	5	-4	3	-6	4	-1

Note: *Eff*: Energy efficiency policy *Ctax*: Carbon tax policy

Considering the energy efficiency policy in the electricity sector, the rebound is present in almost all regions and for the three selected fossil fuels is in the range of 0 to 49%. Regarding the carbon tax policy, there is a negative rebound indicating that this option is more effective but these results cannot be generalised for the rest of the sectors. For the remaining cases, there are some regions that show a higher rebound for the carbon tax policy. Energy intensive industries in EU15, Japan, RoA1 and LACA denote a higher rebound in the use of gas, oil products, and electricity in comparison with the efficiency policy. Other industries show a similar rebound in RoA1 for both policies, but with a higher carbon tax rebound in MENA.

Table 10: Electricity sector: Long-run rebound effect for energy efficiency and carbon tax policies (in percentage for 2050)

Region	USA		EU15		JAPAN		RoA1		EEFSU		MENA		CHINA		LACA		RoW	
Policy	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**	**Eff**	**Ctax**
Coal	29	-57	7	66	3	5	10	-62	5	-66	-3	-164	74	-303	-10	3	1	-6
Gas	28	-136	-1	263	5	337	17	-143	90	-245	87	-300	-	-	48	3	27	-38
Oil_Pcts	-	-	-	-	6		-	-	88	-543	80		-	-	113	-	166	-64

Note: *Eff*: Energy efficiency policy *Ctax*: Carbon tax policy

Table 10 shows the long-run rebound effect for the electricity sector taking into account only the three main fossil fuels used to produce it. In the case of the efficiency policy, there is a higher rebound in the long-run for most of the cases. The short rebound is higher only when the fossil fuel has a lower relative use respect to the others (Coal for LACA, Gas for EU15

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[24] This tax is levied on carbon emissions released by the combustion of fossil fuels, namely coal, gas, oil and oil products.

and Japan). Evaluating both policies in the long-run, the carbon tax policy is less effective in EU15, Japan and LACA. These results indicate that in the electricity sector there is an open possibility to look for a combination of energy efficiency and carbon price policies that should increase the mitigation policy effectiveness.

3.5.3.2 Carbon tax rebounds by type of energy

The change in energy efficiency use induced by a policy can be evaluated for every type of energy by calculating its intensity by unit of output or GDP. This concept is useful to decompose the carbon tax rebound effect when compared to changes of each energy demand. Table 11 shows the regional wide rebound for each type of energy in the short-run along with the share over total energy consumption in million tons of oil-equivalent for 2004. The carbon tax policy is more effective in sectors with lower or negative rebound and high consumption shares. For instance, the importance of oil is reduced given that its main use is feedstock for oil products, as shown by its shares lower than 1%. The effectiveness of the policy is lower in EU15 with a positive rebound effect for all types of energy but oil products. According to table 11 developing countries show a more effective outcome of a carbon tax in terms of a negative rebound.

Table 11: Regional wide rebound for a carbon tax by type of energy and share over total energy consumption (in percentage for 2004)

Region	*Coal*		*Oil*		*Gas*		*Oil_Products*		*Electricity*	
	Rebound	*Share*	*Rebound*	*Share*	*Rebound*	*Share*	*Rebound*	*Share*	*Rebound*	*Share*
USA	0	24	-2	0	-1	23	-2	38	-1	14
EU15	2	13	-9	0	2	24	-50	46	9	17
JAPAN	0	19	-1	1	0	14	-1	51	-2	16
RoA1	-1	16	-4	0	-1	27	-3	39	-3	18
EEFSU	-5	18	-13	0	-7	39	-15	20	-14	23
MENA	-4	4	-12	1	-5	44	-9	41	-8	9
CHINA	-3	57	-5	1	-3	3	-6	26	-5	14
LACA	-3	5	-10	0	-2	28	-7	51	-10	15
RoW	-1	31	-13	0	-2	15	-7	39	-4	14

3.6 Conclusions

The existence of the rebound effect, which may take back energy efficiency improvements, is a matter of concern when considering efficiency and climate policies. However, the evidence for direct and economy wide rebound effects should not be considered as an undermining argument for these kind of policies. On the contrary, it should be used to select industries, which implement those policies according to their potential effectiveness taking into account the rebound estimates.

This paper analyses the subject by means of a global CGE model that considers endogenous technological change and the possibility to induce energy efficient behaviour through carbon price signals. Furthermore, it takes into account additional channels to transmit those signals by using a database with international trade flows and knowledge stocks, proposing some economy-wide estimates based on rebound effect definitions coming from the existent literature.

A first overview is given through the general equilibrium price elasticity of demand, which constitutes one of the elements explaining the rebound effect; however, it should not be taken as a final measure of the phenomenon. The output of a CGE model offers enough information to compute a closer estimate of economy-wide rebounds, taking also into account counterfactual analyses. Instead of implementing a full set of energy efficiency improvements in all sectors at the same time, the estimates consider one energy commodity at a time. Given that there are different technologies related to each kind of energy, that option offers a more precise method for assessing the economy-wide rebound.

Short-run estimates in this study are much higher compared to direct rebound estimations from the existent literature and are in the range of other studies based on CGE models. Long-run estimates are generally higher than short-run ones. Rebound effects are lower for coal, gas, and oil products when they are the result of an isolated policy implemented in only one region, revealing the influence of international trade through prices change signals that eventually affect intermediate and final energy demand. A sensitivity analysis suggests that the rebound effect is more sensible to lower elasticities of supply for fossil fuels and lower inter-fuel substitution than to changes to the elasticity of substitution between capital and energy as long as the latter is below 1.

When energy intensity of GDP is used to estimate a regional-wide rebound, the higher effects are found to be in the use of gas, oil products, and electricity. This aggregate indicator could be used to assess the potential effectiveness of a particular policy in different regions and for specific types of energy, allowing for a detailed policy design that could also contemplate economic development without the trade-off related to climate policy.

In general, a carbon tax policy shows lower rebound effects and therefore should be more effective than an energy efficiency policy. This result is confirmed when using energy intensity variations as proxy for energy efficiency improvements to estimate both the rebound for single sectors by type of energy commodity and for the economy-wide rebound. However, even policy effectiveness may be reduced in some sectors due to a rebound effect following efficiency improvements induced by an explicit carbon price (tax).

This analysis could be enriched with a more detailed description of the energy systems. For instance, having renewable energy sources both in the database and CGE model would allow to better identify the associated rebound effects of each primary energy source. In doing so, it would be possible to understand if clean energies could benefit from the existence of a rebound effect, and therefore, count on an additional element or incentive to foster their development. Finally, it could also be interesting to understand whether subsidies to R&D investments in specific sectors would intensify or weaken rebound effects related to efficiency or climate policies.

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CONCLUSION AND FURTHER RESEARCH

This dissertation analyses the effectiveness of climate policies considering the explicit formulation of ETC in a general equilibrium framework. Including ETC in a CGE model allows combining two important feedback mechanisms that may affect the final outcome of a climate policy. The first one relates to market-price signals that induce economic behaviour. The second refers to ETC and the elements that may induce its evolution. Moreover, the formulation of ETC in a CGE model sets a suitable framework to analyse the rebound effect derived from energy efficiency improvements, which also affect climate policies.

This thesis is divided into three chapters, each one exploring the effectiveness of climate policies from a different perspective. The first chapter considers ETC specifically as biased-technical change in the form of trade-embodied international technology spillovers restricted to imports of machinery and equipment. The net effects of embodied spillovers have been evaluated in combination with different climate and trade policies. Although they are rather moderate at the aggregate level, there are interesting redistributive effects when observed at the sectoral and regional level. A further development of the analysis would be to consider improvements derived from firm heterogeneity to enhance the trade-spillovers representation in the CGE model. This would require refining the biased-technical change parameters estimation extending the data to consider additional countries besides OECD, and also the particular specification of the CGE model.

The second chapter improves the representation of ETC by building sector-specific stocks of knowledge, which accumulate thanks to investments in R&D. The modified CGE model is then used to evaluate the effect of a carbon tax policy implemented worldwide. Including a knowledge stock in the analysis reveals a higher flexibility for countries that can accumulate more knowledge. Developed countries with higher initial knowledge stocks are able to react faster to a carbon tax burden and may also increase their output. In contrast, developing regions carry a higher loss at the beginning but can reduce it as long as they accumulate a significant knowledge stock in the future. A natural extension of the ETC model could be the inclusion of intersectoral and international knowledge spillovers. The parameter estimation for inter-industry spillovers is a crucial aspect that would depend on the empirical model estimation. This should consider the exposure not only to domestic but also to foreign stocks of knowledge. In addition, extending the energy commodities portfolio with renewable sources would provide useful insights about the energy mix following a policy implementation.

The third chapter focuses on the rebound effect by means of the improved ETC model described in the previous chapter. The analysis considers exogenous energy efficiency improvements as well as induced efficiency improvements derived from a carbon tax policy. The carbon tax shows lower rebound effects in most cases and therefore should be more effective than an energy efficiency policy. Therefore, rebound effect estimates should be used to assess the potential policy effectiveness and identify specific types of energy, allowing for a more efficient policy design. As for further research, the use of an extended model with renewable energies would improve the analysis. In addition, further studies could consider whether subsidies to R&D investments in specific sectors would intensify or weaken rebound effects.

Annex A: Description of the ICES model

Introduction

ICES (Inter-temporal Computable Equilibrium System) is a recursive-dynamic, multi-sector and multi-region CGE model of the world economy developed at the Fondazione ENI Enrico Mattei, mainly with the aim of analysing climate change impacts and policies. ICES builds upon the GTAP database and model (Hertel, 1997), and also on the development of GTAP-E (Burniaux and Troung, 2002), which incorporates in the original GTAP model version a more detailed description of energy use. It also offers additional information on greenhouse gases emissions related to fossil fuel combustion and land use.

The main features of the model are:

- Top-down recursive-dynamic model, with more flexible energy substitution;
- Detailed regional and sectoral disaggregation;
- Inter-sectoral factor mobility and international trade, as well as international investment flows;
- Representation of emissions of main GHGs gases: CO_2, CH_4, N_2O;
- A policy module with the representation of a market for emissions permits for CO_2, or a carbon tax on the use of fossil fuels.

As in all CGE models, ICES makes use of the Walrasian perfect competition paradigm to simulate adjustment processes, although some elements of imperfect competition can also be included. The static core of the model is based on different additions to the GTAP-E model designed to assess specific climate change impacts (Bosello *et. al.*, 2006a, 2006b, 2007, 2008; Eboli *et. al.* 2010). The following sections provide a description of the basic structure of ICES. For a complete detail of all the remaining equations, interested readers may refer to Hertel (1997).

Firm's supply side structure

Each industry is modelled as a cost-minimising representative firm, and output prices are given by average production costs. The production structure of the standard GTAP model (Hertel, 1997) has been replaced by the more detailed GTAP-E specification (Burniaux-Truong, 2002), which among other things improves the modelling of the energy production. A more flexible specification, considering inter-fuel and fuel-factor substitution, is linked with a top-down (economic) approach, describing the macro economy with behavioural responses.[25] More specifically, the production process develops in a series of nested functions; a convenient structure to adopt different assumptions about the substitutability between diverse pairs of inputs (see Figure A1 for elasticities of substitutions between nests). The following equations are valid within every region, and for convenience the regional subscripts have been omitted.

The upper-level nested specification of the production tree describes the final output of sector j (Y_j) as a function of a technological index (A_j), the aggregate value added-energy (VAE_j), and the other intermediate inputs (M_j) provided by all sectors, α_j are distribution parameters. The elasticity of substitution for the top nest (σ_M) has been set equal to 0, therefore representing a Leontieff specification.

$$Y_j = A_j \left[\alpha_{VAE,j} VAE_j^{\frac{\sigma_M - 1}{\sigma_M}} + \alpha_{M,j} M_j^{\frac{\sigma_M - 1}{\sigma_M}} \right]^{\frac{\sigma_M}{\sigma_M - 1}} \tag{A1}$$

The lower-levels of the production processes are represented by Constant Elasticity of Substitutions (CES) functions allowing for some degree of substitutability between production factors. Given the distribution parameter δ_{ij}, the aggregate value added-energy output, VAE_j, is produced with Z_i primary factors (i = land, labour, natural resources, and a capital-energy composite-KE), which are allowed to substitute one with the other at the elasticity of substitution σ_{VAE}.

$$VAE_j = \left[\sum_i \delta_{ij} Z_{ij}^{\frac{\sigma_{VAE} - 1}{\sigma_{VAE}}} \right]^{\frac{\sigma_{VAE}}{\sigma_{VAE} - 1}} \tag{A2}$$

Similarly, the capital-energy composite (KE) is produced by combining capital (K) and energy (E) as illustrated by equation A3.

$$KE_j = \left[\alpha_{k,j} K_j^{\frac{\sigma_{KE} - 1}{\sigma_{KE}}} + \alpha_{e,j} E_j^{\frac{\sigma_{KE} - 1}{\sigma_{KE}}} \right]^{\frac{\sigma_{KE}}{\sigma_{KE} - 1}} \tag{A3}$$

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[25] See Burniaux-Truong, (2002) for more details.

Whether capital and energy are complements rather than substitutes is an important issue determining the direction of the aggregate output adjustments to changes in energy prices. Although empirical estimations of the corresponding elasticity parameter (σ_{KE}) vary considerably in size and sign, capital and energy tend to be complements in the short-run and substitutes in the long-run. To account for this aspect, while we assume σ_{KE} to be positive (0.5 for all industries), its value is set to be lower than σ_{VAE} so that the overall elasticity of substitution between capital and energy can still be negative.

Energy (*E*) is modelled as a composite of all energy vectors combining a single type of energy with a composite in pairs according to their particular features. The first composite compounds Electricity (*EL*) with Non-Electric energy (*NEL*) with an elasticity of substitution ($\sigma_{ELY}=1$):

$$E_j = \left[\alpha_{EL,j} EL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}} + \alpha_{NEL,j} NEL_j^{\frac{\sigma_{ELY}-1}{\sigma_{ELY}}} \right]^{\frac{\sigma_{ELY}}{\sigma_{ELY}-1}} \tag{A4}$$

In turn, non-electric energy (*NEL*) is composed of Coal and Non-Coal energy, assuming an elasticity of substitution of $\sigma_{COAL}=0.5$.

$$NEL_j = \left[\alpha_{COAL,j} COAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}} + \alpha_{NCOAL,j} NCOAL_j^{\frac{\sigma_{COAL}-1}{\sigma_{COAL}}} \right]^{\frac{\sigma_{COAL}}{\sigma_{COAL}-1}} \tag{A5}$$

The rest of liquid fossil fuels (*F*) are combined in a composite (*NCOAL*) also following a CES production function with the elasticity of substitution ($\sigma_{FF}=1$):

$$NCOAL_j = \left[\sum_i \beta_{i,j} F_{i,j}^{\frac{\sigma_{FF}-1}{\sigma_{FF}}} \right]^{\frac{\sigma_{FF}}{\sigma_{FF}-1}} \qquad i = \text{oil, gas, oil products} \tag{A6}$$

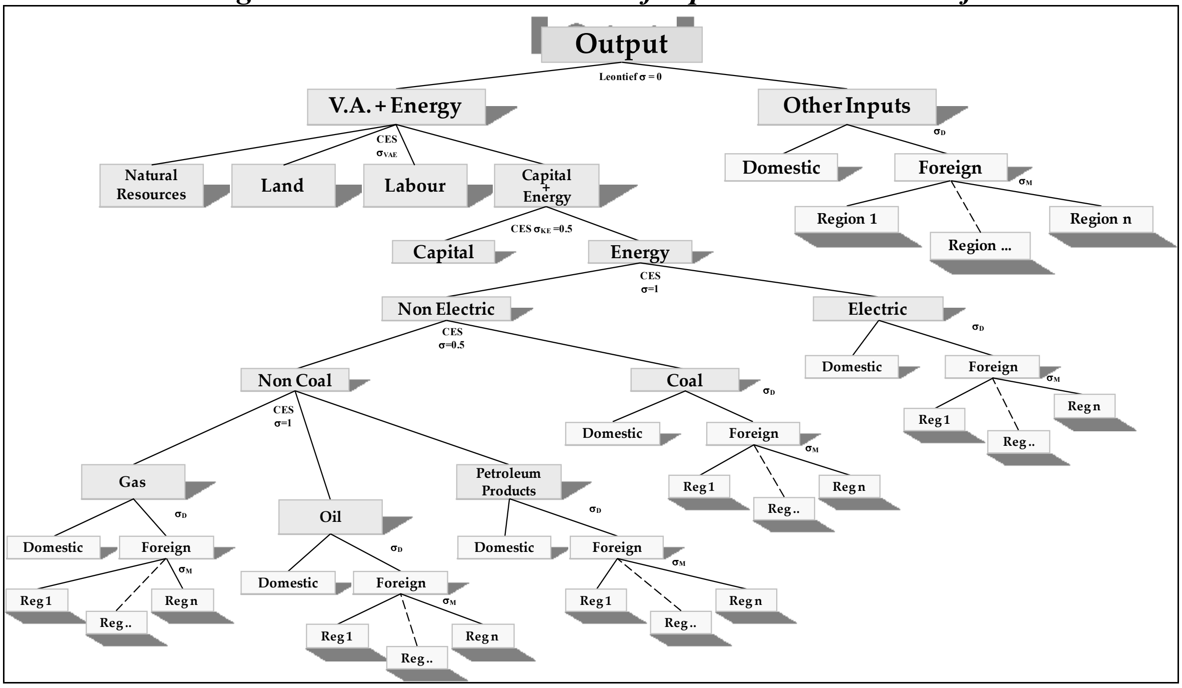
Regarding the source of commodities either final consumption by households of for intermediate use for firms, the "Armington" assumption makes domestic (*DOM*) and foreign (*IMP*) commodities imperfect substitutes, enabling us to account for product heterogeneity.

$$M_i = \left[\alpha_{dom,i} DOM_i^{\frac{\sigma_{dom}-1}{\sigma_{dom}}} + \alpha_{imp,i} IMP_i^{\frac{\sigma_{dom}-1}{\sigma_{dom}}} \right]^{\frac{\sigma_{dom}}{\sigma_{dom}-1}} \tag{A7}$$

Imported commodities are modelled as a composite that combines imports of commodity *i* from all source regions (*s*).

$$IMP_i = \left[\sum_s o_{i,s} Y_{i,s}^{\frac{\sigma_{imp}-1}{\sigma_{imp}}} \right]^{\frac{\sigma_{imp}}{\sigma_{imp}-1}} \qquad \text{(A8)}$$

Figure A1: Nested tree structure for production in sector j



Source: Burniaux and Truong (2002)

Household's demand side

A representative consumer in each region receives income, defined as the service value of national primary factors (natural resources, land, labour, and capital). Capital and labour are perfectly mobile domestically but immobile internationally. Land and natural resources, on the other hand, are industry-specific. That income is used to finance three classes of expenditure: aggregate household consumption, public consumption and savings. The expenditure shares are generally fixed, which amounts to saying that the top-level utility function has a Cobb-Douglas specification.

For the demand side, the traditional GTAP structure has been replaced by the regional household's demand described in McDougall (2003). The top-level demand system of a representative regional household is described by a Cobb-Douglas utility function where the aggregate utility involves the per-capita utility from private and government consumption, and the one from real saving.

The Cobb-Douglas specification is the following:

$$U = CU_P^{\omega_P} U_G^{\omega_G} U_S^{\omega_S} \tag{A9}$$

where U is the per-capita aggregate utility while U_P, U_G, and U_S are respectively the per-capita utility from private and government consumption, and real saving; whilst ω_i represent their distributional parameters.

Real saving is a single commodity deflated by the saving price. Government preferences have the same functional form of the top-level utility function while the demand system of private consumption is split according to a Constant Difference in Elasticities (CDE) functional form (see Figure A2). The CDE demand system is characterized by an indirect utility function of the form:

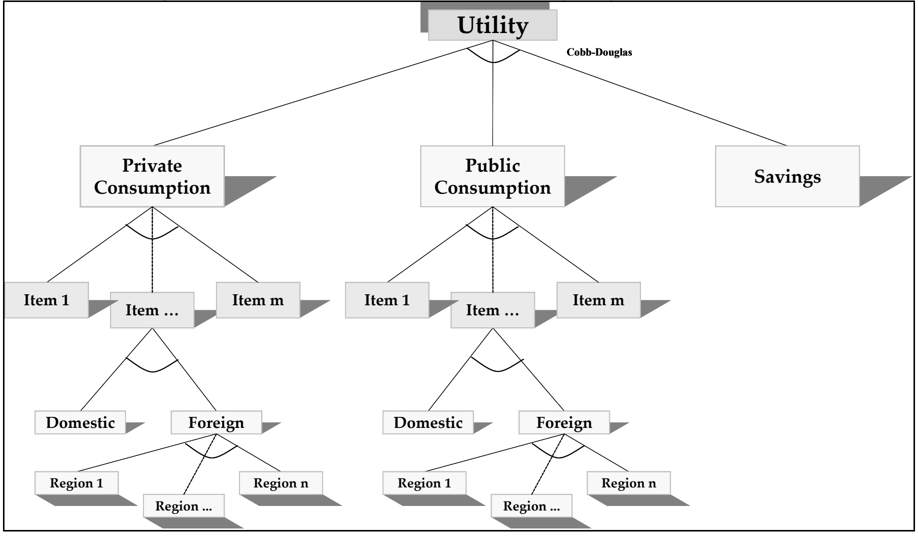
$$1 = \sum_i B_i U^{\gamma_i R_i} \left(\frac{P_i}{X} \right)^{\gamma_i} \tag{A10}$$

with P_i, being the price of commodity i, X the household expenditure, while B_i, γ_i, and R_i are positive parameters. This non-homothetic function enables accounting for possible differences in income elasticities for the various consumption goods. The regional household maximizes the aggregate utility under a budget constraint depending on per-capita income, defined as the service value of national primary factors (natural resources, land, labour, and capital). The budget constraint takes the following form:

$$E_P(P_P, U_P) + E_P(P_G, U_G) + P_S U_S = X \tag{A11}$$

where E_P, E_G are the per-capita expenditure functions; P_P, P_G, P_S the price vectors, and X the per-capita income, defined as the service value of national primary factors (natural resources, land, labour, and capital).

Figure A2: Nested tree structure for final demand



Source: Hertel (1997)

Climate Policy module

ICES incorporates a climate policy module which allows: i) imposing a carbon price/tax on CO_2 emissions coming from fossil fuels use, ii) allocating quotas on those CO_2 emissions, and iii) trading emissions permits among those countries participating in a coordinated mitigation effort. The module specification allows modelling a carbon tax which is levied on CO_2 emissions released to the atmosphere through the use and combustion of fossil fuels. The model accounts for CO_2 emissions by using conversion coefficients indicating the carbon content of fossil fuels (coal, oil, gas and oil products). Indeed, when a productive process involves the combustion of a particular fossil fuel, the model computes the corresponding emissions in carbon equivalent. However, it is assumed that no emissions release occurs when a fossil fuel is used as a feedstock, given that no fuel combustion takes place.

The carbon tax increases the market price of the selected fuel, according to the specific carbon content of each fuel. This formulation allows simulating an Emission Trading Scheme (ETS) in which an emissions reduction quota is assigned to each participating country. Also, countries are allowed to exchange emissions permits at the optimal carbon price according to regional and global emission targets.

Recursive dynamics: Capital and debt accumulation

ICES is a recursive-dynamic model that generates a sequence of static equilibria under myopic expectations linked by capital and international debt accumulation. The dynamic behaviour of ICES has two essential sources. The first is endogenous as it is governed by capital and debt accumulation while the second one is based on exogenous external forecasts of endowments and productivities. Growth is driven by changes in primary resources (capital, labour, land and natural resources) with 2001 as the initial year (GTAP 6 database).[26] Dynamics are endogenous for capital and exogenous for others primary factors. Capital accumulation is the outcome of the interaction of: i) investment allocation between regions and ii) debt accumulation as described below.

Regional investments and capital stocks are determined as follows. Savings are a constant fraction of regional income. All savings are pooled by a virtual world bank and allocated as regional investments, on the basis of the following relationship:

$$\frac{I_r}{Y_r} = \phi_r \exp\left[\rho_r\left(r_r - r_w\right)\right] \tag{A12}$$

where: I_r is regional annual investment, Y_r is regional income, r_i is regional and world returns on capital, ϕ_r is a given parameter that represents the average propensity to save and ρ_r is a flexibility parameter that determines the sensitivity of investment supply to return differentials. The rationale of equation (A12), which has been adopted from the ABARE GTEM model (Pant, 2002), is that whenever returns on capital do not differ from those in the rest of the world, investments are proportional to regional income, like savings are. In this case, current returns are considered as proxies of future returns. If returns are higher (lower) than the world average, then investments are higher (lower) too. Investments affect the evolution of capital stock, on the basis of a standard relationship with constant depreciation over time:

$$K_r^{t+1} = I_r^t + (1-\delta)\cdot K_r^t \tag{A13}$$

Equation (A12) does not ensure the equalization of regional investments and savings, and any region can be creditor or debtor vis-à-vis the rest of the world. Because of accounting

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[26] Dimaranan (2006).

identities, any excess of savings over investments always equals the regional trade balance (*TB*), so there is also a dynamics for the debt stock, similar to (A13), but without depreciation:

$$D_r^{t+1} = TB_r^t + D_r^t \tag{A14}$$

Foreign debt is initially null for all regions and then evolves according to (A14). Foreign debt service is paid in every period on the basis of the world interest rate r_w .[27]

Baseline simulations

To project the model from the benchmark for 2001 to a future year, we introduce externally estimated values in the calibration-data. These relate to key socio-economic variables such as population, stocks of endowment factors, land and labour productivity which are exogenous variables in the model. In this way we obtain a reference baseline scenario. Moreover, it is possible to produce a counterfactual scenario by perturbing the baseline with additional exogenous shocks to perform conventional comparative static exercises. The comparison between the baseline and the counterfactual scenario allows quantifying the net effect of exogenous changes in selected variables. This effect results in variation of endogenous variables in the model such as: i) cost of the policy; ii) regional GDP and CO_2 growth rates; iii) income and regional prices, and iv) regional demand quantities and composition (since they depend on national income and relative prices).

The baseline or Business as Usual (BAU) scenario from 2001 to 2050 has been generated using different sources for the exogenous drivers mentioned above. Population forecasts for 2050 are taken from the World Bank[28] and the same growth rates are applied to regional labour stocks. Estimates of land productivity are obtained from the IMAGE model (IMAGE, 2001). Labour productivity has been calibrated to replicate A2 scenario from the Intergovernmental Panel for Climate Change (IPCC) (Nakicenovic, N. and R. Swart, 2000 and IIASA, 2007).

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[27] This is set in the model by equating global savings and investments.

[28] Available at http://devdata.worldbank.org/hnpstats/. Population does not directly affect labour supply, but affects household consumption, which depends on per capita income.

Natural resources stocks are endogenously estimated in the model by fixing their prices during the baseline calibration stage, while for further simulations those estimated stocks become an exogenous input in the model. This methodology was useful for setting an increasing trend in prices for fossil fuels (oil, coal and gas) using EIA forecasts (EIA, 2007), whereas for other industries (forestry, fishing) its resource price is changed in line with the GDP deflator.

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Estratto per riassunto della tesi di dottorato

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Dottorato: Scienza e Gestione dei Cambiamenti Climatici

Ciclo: 23°

Titolo della tesi: Climate change policies and endogenous technical change in a general equilibrium modelling framework. Trade Spillovers, Knowledge Stocks and Rebound Effects.

Abstract: This work is structured into three chapters, each one exploring the effectiveness of climate policies considering the formulation of endogenous technical change (ETC) from different perspectives. Including ETC in a computable general equilibrium model allows combining important feedback mechanisms that may affect the final outcome of a climate policy. The first chapter considers ETC specifically as biased-technical change in the form of trade-embodied international technology spillovers, restricted to imports of machinery and equipment. The second chapter improves the representation of ETC by building sector-specific stocks of knowledge, which accumulate thanks to investments in R&D. The third chapter focuses on the rebound effect by means of the improved ETC model described in the previous chapter.

Estratto: Diviso in tre capitoli, questo lavoro esplora l'effettività delle politiche climatiche in relazione al tema del progresso tecnico endogeno (ETC), sotto varie prospettive. L'inclusione dell'ETC in un modello di equilibrio economico generale consente la combinazione di importanti meccanismi di feedback in grado di incidere sul risultato finale di una politica climatica. Il primo capitolo elabora il progresso tecnico nella forma di spillovers tecnologici derivanti dal commercio internazionale di macchinari e di capitale. Il secondo capitolo presenta una più completa rappresentazione dell'ETC introducendo nel modello degli stock di conoscenza specifici per ogni settore, accumulabili tramite investimenti in ricerca e sviluppo. Il terzo capitolo, partendo dal modello ETC sviluppato nel capitolo precedente, si concentra sui cosiddetti effetti di rebound.