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Summary

This paper uses a dynamic CGE model to assess the intertemporal and spatial dimension of technology spillovers embodied in international trade within a climate and trade policy framework. Three are the main contributions of the study. First, to include endogenous factor-biased technical change based on trade flows in a CGE model, particularly for energy and capital. Second, to analyse the implications of specific spillovers embodied in trade of capital goods (machinery and equipment), and third, to highlight the implications of accounting for indirect effects induced by spillovers. 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, there are important international and intersectoral redistribution effects due to technology transfers represented as embodied spillovers.

Keywords: Computable General Equilibrium Models, Climate Change, Economic Growth, Technological Spillovers

JEL Classification: C68, E27, O12, Q54, Q56, O33

This paper is part of the research of the Climate Change and Sustainable Development Programme of the Fondazione Eni Enrico Mattei. We would like to thank Carlo Carraro, Marzio Galeotti, Valentina Bosetti and Melania Michetti for helpful comments and discussions.

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Abstract

This paper uses a dynamic CGE model to assess the intertemporal and spatial dimension of technology spillovers embodied in international trade within a climate and trade policy framework. Three are the main contributions of the study. First, to include endogenous factor-biased technical change based on trade flows in a CGE model, particularly for energy and capital. Second, to analyse the implications of specific spillovers embodied in trade of capital goods (machinery and equipment), and third, to highlight the implications of accounting for indirect effects induced by spillovers. 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, there are important international and intersectoral redistribution effects due to technology transfers represented as embodied spillovers.

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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 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.

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 (2012), 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 take into account 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).

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 (2012). The model has been calibrated taking into account the influence of machinery and equipment imports only in capital and energy-biased technical change.

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.[1] 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.

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 (2012). The choice of this study is 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 (2012) 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.

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[1] The description of the ICES model and the aggregation detail is in Annex A.

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.

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

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:

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

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 (2012) 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 ($\boldsymbol{\hat{a}_i}$) 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).[2]

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

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

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 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 in sector j ($E_{j,r}$) increases with the scale of the sector's output, given by $Y_{j,r}$. The second term describes the substitution effect. An increase in the price of energy p_E compared to the output price p_Y 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 technical change of energy, represented by the parameter ($a_{E,j,r}$) 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.

$$E_{j,r} = Y_{j,r} + \sigma(p_Y - p_E) - (1 - \sigma) \cdot a_{E,j,r} \tag{5}$$

In the same study, Carraro and De Cian (2012) 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.

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 $CS_{j,r}$	**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

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 reverse 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.[3] 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.

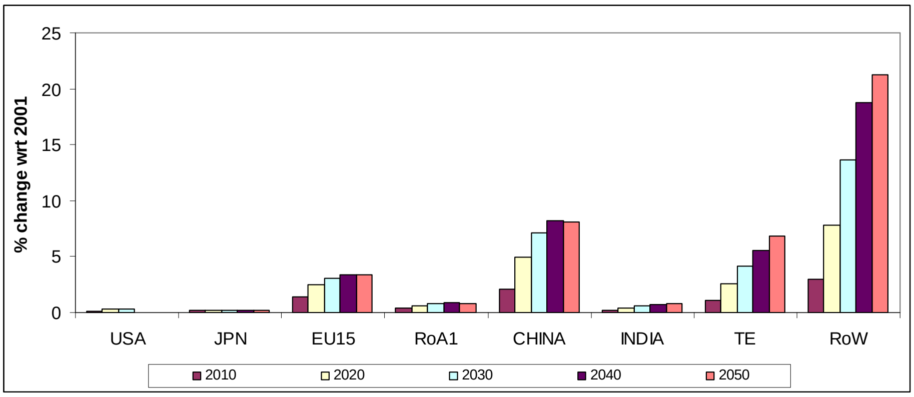

Figure 1: Capital-biased technical change growth in the baseline

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 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

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[3] 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.

also reflected in a reduction of relative input prices in destination regions, where production is reallocated.

Table 8: Spillover effects on GDP, emissions and output 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
Sectoral Output								
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.

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.

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%

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%

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%

5.4 Sensitivity analysis

The size of the capital-energy substitution elasticity (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 ($\sigma=0.38^*$) 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).

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.

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 developed 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.

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 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, Dimaranan, 2006). 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.

Model aggregation and BAU scenario

ICES is flexible enough to be used in different regional and sectoral aggregations, and for this particular model formulation we use 8 regions and 12 sectors described in table 1, chosen specifically for the analysis of technology spillovers in a dynamic context . In this aggregation the sector Machinery and Equipment is the vehicle of international technology spillovers and there is a distinction of regions as source (OECD) or destination (Non-OECD) of spillovers.

Sectors		
Industries	***Energy***	***Services***
Agriculture	Coal	Market Services
Chemicals	Oil	Non-Market Services
Metal Products	Gas	
Machinery & Equipment	Oil Products	
Other industries	Electricity	

Regions	
Code	***Description***
USA	United States
JPN	Japan
EU15	European Union – 15
RoA1	Rest of Annex 1 countries
CHINA	China
INDIA	India
TE	Transition Economies
RoW	Rest of the World

Table A1: ICES sectoral and regional aggregation

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[4] 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). 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).

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

No.	*sector*	*Description*	*Comprising old sectors*
1	Agriculture	Agriculture	Paddy rice; Wheat; Cereal grains nec; Vegetables, fruit, nuts; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec; Cattle,sheep,goats,horses; Animal products nec; Raw milk; Wool, silk-worm cocoons; Forestry; Fishing; Meat: cattle,sheep,goats,horse.
2	Coal	Coal	Coal.
3	Oil	Oil	Oil.
4	Gas	Gas	Gas; Gas manufacture, distribution.
5	Oil_Pcts	Oil Products	Petroleum, coal products.
6	Electricity	Electricity	Electricity.
7	Chemicals	Chemicals	Chemical,rubber,plastic prods.
8	MetalProducs	Metal Products	Ferrous metals; Metals nec; Metal products.
9	Machequip	Machinery & Equipment	Machinery and equipment nec.
10	Oth_ind	Other Intdustries	Minerals nec; Meat products nec; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products; Textiles; Wearing apparel; Leather products; Wood products; Paper products, publishing; Mineral products nec; Motor vehicles and parts; Transport equipment nec; Electronic equipment; Manufactures nec.
11	MServ	Market Services	Water; Construction; Trade; Transport nec; Sea transport; Air transport; Communication; Financial services nec; Insurance; Business services nec; Recreation and other services; Dwellings.
12	NMServ	Non Market Services	PubAdmin/Defence/Health/Educat.

Table A2: Detailed sectoral aggregation

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