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Enrica De Cian, *School for Advanced Studies in Venice Foundation and Fondazione Eni Enrico Mattei*

Corso Magenta, 63, 20123 Milano (I), web site: www.feem.it, e-mail: working.papers@feem.it

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Summary

This paper analyzes two possible methodologies of modeling international technology spillovers in a climate-economy CGE model. Technological change, by affecting productivity, energy and carbon intensity, eventually influences the amount of CO2 emissions, the costs and the timing of the policies targeted at their reduction. Technological change is here defined so as to include also the diffusion and adoption phase. In an increasingly integrated world, new products and technologies developed in one region will eventually diffuse internationally. The two approaches described in this paper are based on two mechanisms used to model technological change in climate models: learning curves, total factor productivity and the autonomous energy efficient improvement parameter. This paper considers spillovers mediated by international trade in capital goods. In particular, it looks at how imports machinery and equipments from the OECD countries can affect the technology variables related to CO2 emissions: learning rates in the first approach, productivity, energy and carbon intensity in the second one.

Keywords: Climate Policy, International Trade, Learning Curves, International Technology Spillovers, Biased Technical Change

JEL Classification: F18, 033, Q54, Q55

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Address for correspondence:

Enrica De Cian
Fondazione Eni Enrico Mattei
Campo S. Maria Formosa 5252
30122 Venezia
Italy
E-mail: enrica.decian@unive.it

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Abstract

This paper analyzes two possible methodologies of modeling international technology spillovers in a climate-economy CGE model. Technological change, by affecting productivity, energy and carbon intensity, eventually influences the amount of CO_2 emissions, the costs and the timing of the policies targeted at their reduction. Technological change is here defined so as to include also the diffusion and adoption phase. In an increasingly integrated world, new products and technologies developed in one region will eventually diffuse internationally. The two approaches described in this paper are based on two mechanisms used to model technological change in climate models: learning curves, total factor productivity and the autonomous energy efficient improvement parameter. This paper considers spillovers mediated by international trade in capital goods. In particular, it looks at how imports machinery and equipments from the OECD countries can affect the technology variables related to CO_2 emissions: learning rates in the first approach, productivity, energy and carbon intensity in the second one.

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1 Introduction

Technological change has become a relevant component of long-term climate change policies. Anthropogenic CO_2 emissions are the product of population,

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[*] School for Advanced Studies in Venice Foundation and Fondazione ENI Enrico Mattei

economic activity per capita, energy use of economic activity and the carbon intensity of energy used. In a growing world economy, reducing economic activity does not seem an appealing strategy. The other two options available are reducing the energy intensity and/or the carbon intensity of economic activities. The economic and environmental gains of these behaviors are not under discussion: the issue is at what costs. Technological change plays a key role in making these strategy more attractive from an economic perspective. Technological change refers to the whole process of invention, development or innovation and diffusion or adoption of new products, pieces of equipment and processes.

The development of more advanced and cleaner technologies needs R&D expenditure, capital investments and knowledge accumulation. World R&D activity is concentrated in the OECD countries. To put things into perspective, the major future polluters, China, India and Brazil have lower capacities of affording R&D expenditure and costly investments. This implies less technological progress where it would be needed the most. The lack of domestic knowledge accumulation may be partially compensated by the knowledge technology spillovers mediated by trade. The process of diffusion plays an important role in spreading the benefits of technological change from innovating to non innovating countries. Technology diffusion can take place through international trade in capital goods such as machinery and equipments. It is part of the process of technological change as it represents a stage of further commercialization and adoption of the new technologies developed in the OECD. The diffusion process is reflected in the purchase of new goods and imports are the purchase of foreign goods.

Technological change has received increasing interests from climate-economy modelers, the reason being the significant effect it has on the timing and the costs of climate change mitigation (Loschel, 2002; Carraro, Gerlagh, van der Zwaan, 2003). From a theoretical perspective, endogenous growth theory has also emphasized the role of technological progress in sustaining long-term growth (Arrow, 1962; Romer, 1986, 1990). In this literature, technological progress is determined endogenously by either R&D investments or technology spillovers, such as learning-by-doing and R&D externalities. Spillovers are deeply related to the nature of technology and knowledge as partially public goods. So far modelers have mostly focused on cluster-technologies, intra-firms and intra-industry spillovers. Fewer are the attempts in modeling international technology diffusion. From a climate perspective, whether technological change and technology spillovers lead to CO_2-reducing behavior is a key issue. Two research questions drive this study: first, how trade openness and international spillovers influence domestic technological progress. Second, whether the resulting technological change is energy and carbon saving or using. In particular it looks at how imports machinery and equipments can affect those variables that are related to the production of CO_2: productivity, energy and carbon intensity.

Computable-general equilibrium models (CGE) have become one of the modeling tools that can be used to assess the economic impacts of climate policies. Being multi-sector and multi-country models, they particularly suit the study of international trade, and the impact of technology diffusion across sectors and countries. For these reasons, CGE models seem to be the natural setting where to study spillovers embodied in the trade of goods.

The reminder of the paper is organized as follow. Section 2 will define the theoretical background to relate the literature on international trade and endogenous growth to climate change mitigation. It proceeds with the description of the two mechanisms that could be used to model international technology spillovers: the learning curve approach and the technology parameters approach. Section 3 investigates the empirical feasibility of the two approaches outlined, as their actual implementation would require an estimates of the key parameters. The goal of such estimates would be to provide some guidelines for an improved specification of international technology spillovers in a CGE model. The resulting framework could be used to analyze the effects of climate and trade policies in the presence of international technology spillovers. Such a model could capture further interactions between trade and climate policies. Trade policies such as trade liberalization in capital goods could have the side effect of promoting the diffusion of emission-saving technologies and thus to make technology progress available to the non innovating countries. Which sectors are to be liberalized first becomes important for the degree of technology diffusion. Finally, section 4 summarizes and concludes.

2 Theoretical background

The topic of international technology spillovers and their implications on productivity, energy and carbon intensity is at the crossroad between different literatures. This first part will present a selective review, highlighting the concepts that are important for the study of international technology spillovers and technological change in climate-economic models.

2.1 Some definitions

Binswanger and Ruttan (1978) provide a precise definition of technical change, which should be distinguished from technological change. Namely, technical change is defined as a change in the techniques of production at the firm or industry level that results both from R&D and from learning by doing (innovation). Technological change instead is the application of new knowledge of scientific engineering agronomic principles of techniques of production across a broad spectrum of economic activity. Despite this technical distinction, the current literature does not rely on this terminology very strictly and the two terms are often used interchangeably. Another widely used classification is the Schumpeterian distinction of technological progress into the three stages of invention, innovation and diffusion.

Induced technical change was first introduced by Hicks (1932) as the development and the diffusion of any new technology due to (induced by) a change in relative factor prices. The price change can be due to both policy changes and economic condition variations. In climate-models this term usually refers to the effect of a price change due to climate policies such as carbon taxes. Endogenous technical change is used in a modeling context to indicate technical or technological changes that are determined inside the model (Grossman and Helpman, 2001; Sijm, 2004). Technological change is neutral if it shifts the unit isoquant inward without affecting the shape. Technological change is biased toward an input if there is a change in the slope of the isoquant.[1] Binswanger and Ruttan (1978) define the input bias as the rate of change in the factor share at constant prices, where the factor share $Si(t)$ is defined as the value of an input over total costs :

$$Si(t) = Pi(t)Vi(t)/P(t)Q(t)$$

$$\text{Biases} = \dot{Si}(t)/Si(t) = \widehat{Pi} + \widehat{Vi} - \widehat{P} - \widehat{Q} = dlog(Vi(t)/Q(t)) - dlog(P(t)/Pi(t))$$

$$\begin{cases} \dot{Si}(t)/Si(t) \geq 0 & \text{i-using} \\ \dot{Si}(t)/Si(t) \leq 0 & \text{i-saving} \\ \dot{Si}(t)/Si(t) = 0 & \text{i-neutral} \end{cases}$$

In words, technological change is i-saving if the input share decreases at constant factor prices. The presence of spillovers is deeply related to the nature of technology and knowledge as partially public goods. Technology spillover, or knowledge spillover, is defined as technological progress available at a lower than the original cost paid by the inventor (Griliches, 1979). Weyant and Olavson (1999) define spillovers as any positive externality that results from purposeful investments in technological innovation or development. They describe different forms and level of spillovers. Technological spillovers can be direct or disembodied (pure knowledge spillovers concerning the impacts of R&D of others) and indirect, embodied in new capital goods. There are also intertemporal spillovers, occurring over time, with experience and knowledge accumulation. They are also called learning by doing or learning by searching spillovers. As for the spatial level, spillovers can take place across firms, industries or national boundaries.

2.2 Technological change and climate change

Whether technological progress is modeled as exogenous or endogenous affects the cost of climate policies. Simulations of CO_2 stabilization scenarios with different types of models have shown how the presence of endogenous technological change affects the availability, the timing and the cost of climate policies.[2]

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[1] For further definitions of biased technological change see appendix A.

[2] For a review of these studies see Loschel(2002), Edenhofer et al. (2005), Carraro, Gerlagh and van der Zwaan (2003).

Technological change can affect CO_2 emissions and reduction through several channels. Kaya's identity decomposes CO_2 emissions into its major determinants

$$CO_2 = \frac{GDP}{POP} * \frac{energy}{GDP} * \frac{CO_2}{energy} * POP \tag{1}$$

For a given level of output, CO_2 reduction can come from lower:

- energy use *per se*;
- energy use per unit of output;
- CO_2 emissions per unit of energy;

For a given level of output, carbon emissions can be reduced by substituting energy for other inputs (energy saving), by reducing the energy used per unit of output (energy efficiency gains) or by curbing carbon emissions per unit of energy used (carbon intensity gains). The first dimension (energy use) is mostly related to socio-economic forces such as population, output growth and economic activity while the last two depend more on techno-economic forces (Bosetti, Galeotti and Carraro, 2005).

Technological change (TC) can have an impact on CO_2 emissions through the three dimensions described above (Galeotti and Carraro, 2003):

- On the supply side, TC may affect the energy efficiency of existing technologies;
- TC can reduce the cost of low-carbon emitting technologies, making them more competitive;
- TC can improve energy efficiency in the end-use sector through product and process innovation;
- TC, by increasing productive, can trigger a positive effect on the scale of the economy.

2.3 Endogenous growth theory, trade and international technology spillovers

The new growth theory has started looking into the black-box of the Hicksian-neutral technological progress. The endogenous growth theory has emphasized the role of learning by doing and knowledge externalities (Arrow, 1962; Romer, 1986); the theory of endogenous technical change departs from the assumption of competitive markets and introduces monopolistic competition where investment in research and development is a profit-driven activity (Romer,1990; Grossman and Helpman, 2001). Either there is continuous innovation that increases the quality or the quantity of existing goods, or there are knowledge-technological externalities coming along with the process of capital and knowledge accumulation that prevent the decreasing marginal returns on capital to set in.

Grossman and Helpman (2001) develop a model of endogenous technological change suitable for the study of the relationship between endogenous growth and international trade. They consider research as an economic activity driven by economic incentives. There is a manufacturing sector that produces the final good for consumption using the intermediates developed by the innovation sector. In this context productivity growth (output per unit of primary inputs) is represented by the number[3] of intermediate varieties. A country grows more when it devotes more resources to the innovation sector, which is defined as the creation of new intermediates varieties. Research helps building up the stock of public knowledge that reduces the effective input-requirements per unit of output.

Trade can have an impact on domestic productivity, energy and carbon intensity through several channels (Grossman and Helpman, 2001):

1. Pure knowledge effect, as a wider transmission of knowledge increases the stock of global knowledge;
2. Communication and imitation opportunities are enhanced;
3. Competition between innovators that eliminates duplication of research;
4. Increased market size leads to more profits, more R&D spending, but also to tougher competition that lowers profits;
5. Increased availability of intermediates inputs and capital equipments;
6. Reallocation of resources across sectors and structural change.

When the first three linkages are activated, countries can benefit from a scale effect because they pool their effort in developing a global stock of knowledge that can feed invention and innovation in all countries. Knowledge is the input of the innovation process and of endogenous technical change. International trade can increase the availability of this input. International flows of workers, the exchange of engineers and information may ease the acquisition of new methods of production. Labor mobility disseminates the knowledge that workers have acquired in different firms and thus change the endowment of human capital. The stock of human capital affects the absorptive capacity, that is the ability of assimilating and adapting foreign technologies. Trade increases the mobility in cleaner capital and in cleaner goods. If countries are integrated through trade, participation in the world economy gives access to a larger variety of inputs, machineries and capital equipments. International trade enlarges the scale of economic activity, but it also has a structural effect. Trade induces changes in the profitability of certain sectors and, eventually, it can induce a change in the energy mix. Whether trade and growth are energy and carbon saving

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[3] In the quality-ladder variant, productivity is increasing in the quality of inputs. However, the major results do not change.

or not depends on how they influence the reallocation of resources toward less energy-intensive sectors, such as services.

Another important channel of international transmission of knowledge and technology has been opened by the rapid diffusion of multinational enterprises (MNEs) and the resulting foreign direct investments (FDI). Aitken and Harrison (1999) summarize the major channels by which FDI could affect domestic productivity: introduction of new products and processes, imitation and competition.

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, technological and institutional development. Moreover, not all types of transfers require the same effort. Material transfers (e.g. seeds and machineries) do not require particular abilities. Design transfers (e.g. blueprints, formulas and handbooks) need more engineering capacity. Capacity transfers (e.g. scientific knowledge, technical capacity or capability) can be benefit from only in the presence of skills and competencies to evaluate and use technical information. They often require tacit knowledge about production processes that cannot be transferred with capital equipments (Binswanger and Ruttan, 1978). Potentialities of reducing these barriers come especially from those transactions that involve human contact and personal relationships. The Kyoto's mechanisms of Clean Development (CDM) and Joint Implementation (JI) may be an example. FDI and joint venture are another type of link that involves personal contacts. Trade barriers can also hinder technology diffusion. In this context, trade liberalization acquires a further role and which sectors are liberalized first may have implications in term of the degree of technology diffusion.

The presence of international trade may also influence the way domestic policies work. For example, induced technological change where climate policies are more stringent may lead to higher investment in clean capital and cleaner methods and processes of production. Countries committed to climate change may eventually gain a comparative advantage in cleaner machineries and equipments. In a open trading system, this relatively abundance in clean capital would affect the pattern of trade and could lead to an expansion of the clean capital intensive good (composition effect). Moreover, the relative price change induced by climate policies could increase the profitability of cleaner production techniques (technique effect) (Copeland and Taylor, 2003). Trade acts like a further possibility of production that allows countries to specialize in the sector where they have a comparative advantage and to buy goods outside their production possibilities. If more technology-advanced goods are produced in developed countries, developing countries still can import them and reap the benefits of foreign innovation and technological progress.

Trade in different classes of goods leads to different degree of knowledge spillovers because technology intensity varies across sectors, leading to different degrees of embodied technology. An exampl of technology -intensive goods are capital goods. They will be the object of the next section.

2.3.1 Trade in capital goods

Endogenous growth theory views technology as a stock of knowledge. Being technological change the application of new knowledge to production processes, the cumulative production of capital goods can approximate technological progress (Arrow, 1962). The development of new capital goods and the use of new equipment and machineries in the manufacturing and in the industrial sector are considered the major sources of technological progress (Jaffe, Newell and Stavins, 2005). Trade of such goods is thus expected to generate indirect international spillovers of the technology embodied in them. In fact, the use of capital goods implies the acquisition of the knowledge that actually enables the use of these goods. Trade in capital goods can be taken as a proxy of international technology spillovers.

The literature on trade and growth has emphasized the role of equipment and machinery imports. DeLong and Summers (1991) found that equipment investments have a higher impact on growth than non equipment investments. Mazumdar (2001) differentiated between domestic and imported equipment, finding a stronger impact for imported capital goods. The intuition is that more spillovers are likely to stem from goods that are relatively intensive in R&D. A shown in table 1, OECD countries concentrate most of their R&D expenditure on machinery and equipment.

ISIC REV. 3	1999
Total business sector 1-99	100
Food products, beverages and tobacco 15-16	1.3
Textiles, textile products, leather and footwear 17-19	0.4
Chemical, rubber, plastics and fuel products 23-25	15.9
Machinery and equipment 29-33	35

Table 1: Business R&D expenditure by sector. Source: OECD STAN statistics, 2005

Table two shows that the composition of bilateral exports from OECD to the bigger developing countries, China, India and Brazil, is concentrated on machinery and equipment, which accounts for about 40% of total bilateral trade flows.

ISIC REV. 3	1999
Food products, beverages and tobacco 15-16	2.104
Textiles, textile products, leather and footwear 17-19	5.07
Chemical, rubber, plastics and fuel products 23-25	19.49
Machinery and equipment 29-33	40.04

Table 2: Bilateral export flows between OECD and China, India, Brazil all together. Source: OECD STAN Bilateral Trade Database, 2005

Table three provides the same information of table two but in terms of percentage composition with respect to the total stock of trade defined as the cumulative trade exports from 1988 to 2003.

OECD Exports stock (1988-2003)	Brazil	China	India
Machinery and equipment nec (29 ISIC-REV.3)	17.10	19.00	18.24
Electronic equipment (30-33 ISIC-REV.3)	23.96	23.70	14.97
Motor vehicles and parts (34 ISIC-REV.3)	9.32	4.52	2.98
Transport equipment nec (35 ISIC-REV.3)	7.76	4.91	4.98

Table 3: Bilateral export stock OECD-China,India,Brazil.Source: OECD STAN Bilateral Trade Database, 2005

The major suppliers of capital goods are the bigger innovators. These figures are consistent with the study of Eaton and Kortum (2001) who found a positive correlation between R&D intensity, specialization in machinery and equipments and their production and export. Trade in machinery and equipments can be expected to be a major channel of embodied spillovers from developed countries, where capital goods are improved, to the developing ones, where a big share of these goods is imported. Developing countries, the major polluters, have lower capacity of affording R&D expenditure and costly investments. International technological diffusion can partially reduce this divide by contributing to the accumulation of capital and knowledge. Imports of capital goods increase the stock of knowledge and technology. Imports of machinery and equipments in the developing countries from rich countries, where the technology embodied in these capital goods moves forward, may eventually trigger technological progress in the importing countries. Some studies did find that, in the presence of endogenous technological change, cleaner technologies developed in industrialized countries in response to climate policy spread to countries not committed to emissions reduction (Loschel, 2002). The degree of technological spillovers is related to the level of capital imports, which in turns depends on country specific trade policies.

2.4 Climate-economy-CGE models and technological change

2.4.1 Sources of endogenous technical change

Two mechanisms have been widely used to model endogenous technical change: R&D investments and R&D externalities or learning by doing (LBD). R&D expenditure and LBD capture two different types of learning process. Whereas R&D investments are profit-driven and therefore costly, LBD is free as it occurs with capital accumulation and experience. The idea of knowledge accumulation as an unintentional process was developed by Arrow (1962): the accumulation of knowledge is a by-product of the manufacturing of capital goods. This allows the presence of knowledge in constant-return-to-scale world. Romer (1986) instead considered the firm as rationally investing in R&D, creating private knowledge, appropriable by the firm only, and public knowledge, freely available to everybody. In principle both types of learning could coexists, providing a more complete description of technological change as a process determined by both intentional and unintentional learning.

The R&D approach treats knowledge as a distinct input in the production function, with its own accumulation equation depending on depreciation and R&D expenditures. R&D generates spillovers that break diminishing returns and thus allow sustained growth. A production function with both R&D investments and externalities can be specified as in Goulder and Schneider (1999):

$$Y_t = A(R_{et})F_t(K_t, L_t, R_{it}) \text{ where } R_{it+1} = (1-\delta)R_{it} + I_{it}$$

Re is the externality from which firms benefit freely whereas *Ri* is the appropriable knowledge.

The notion of LBD has been developed further by the learning curve literature. This approach relates the investment costs of a technology to the production and manufacturing of the technology, to the R&D stock or expenditure and/or to the use of the technology (IEA, 2000). These three factors give rise to three different concepts of learning: learning by doing, learning by searching and learning by using. Cumulative installed capacity can be considered a proxy for the experience accumulated during the production and the manufacturing of the technology and thus of learning by doing. Cumulative R&D expenditure can approximate the stock of knowledge and thus learning by searching for a certain technology. Investment costs of a technology can be a decreasing function of the cumulative installed capacity only, or of the cumulative R&D expenditure as well, giving rise respectively to a one-factor and two-factors learning curve.

The speed of learning by doing can be measured by the learning rate, defined as the percentage improvement of a new technology, usually the percentage cost change that occurs with the doubling of the cumulative capacity (Soderholm and Sundqvist, 2003). A learning rate of 0.2 means that when the cumulative capacity doubles the cost of the technology declines by 20 percent. A learning curve with LBD looks like:

$$C_{it} = a(CC_{it})^{-b} \tag{2}$$

where a is the specific unit cost at unit cumulative capacity ($t = 0$), b is the learning index, CC_{it} is cumulative capacity of a technology at time t and C_{it} is the unit investment cost at time t of technology i. A learning curve in a specific technology can be integrated in a production function where $(CC_{it})^{-b}$ is assumed to represent its state of knowledge at time t in sector i (Soderholm and Sundqvist, 2003). For example, assuming a neutral technical change coefficient proportional to the cumulative capacity, $A_{it} = \beta^{-1}(CC_{it})^{-b}$, a production function with LBD could be formulated in the following way:

$$Y_{it} = \beta^{-1}(CC_{it})^{-b} F(K_{it}, L_{it}, E_{it}) \tag{3}$$

Since experience is a cumulative variable, knowledge at time t is likely to underestimate the total weight of experience. The productivity parameter A_{it} can be better approximated by the new capacity installed at time t, NC_{it}, normalized with respect to the average learning acquired up to that point, $\sum(aCC_{it}^{-b})$ (Gerlagh et al., 2000):

$$A_{it} = \beta^{-1}(NC_{it}/\sum(aCC_{it}^{-b}))$$

and thus

$$Y_{it} = \beta^{-1}NC_{it}/\sum(aCC_{it}^{-b})F(K_{it}, L_{it}, E_{it})$$

Both the R&D externalities[4] and the learning curve approaches can be seen as an application of the Helpman and Krugman (1985) model of economies of scale with external effects. This model allows for increasing return to scale at the industry level whereas individual firms preserve constant return to scale. The production function can be seen as composed of two blocs:

$$F(v_i, E_i) = F(v_i)B(E_i)$$

where v_i are inputs, $F(v_i)$ is a standard constant return to scale production function and $B(E_i)$ is a factor amplifying the productivity of $F(v_i)$. For example, it can represent international spillovers. In this setting, firms set prices according to marginal costs $p = C(w_vi, q)$, but the effective cost is $p = c(w_vi, q)/B(E_i)$. In the two approaches considered in this section:

$$B(Ei) = \begin{cases} \beta^{-1}(CCit)^{-b} & \text{with LBD} \\ A(Re_t) & \text{with R\&D externalities} \end{cases}$$

Helpman and Krugman show that there exist further gains from trade if the magnitude of the external effect E_i is bigger under free trade than in autarky.

2.4.2 Technological change in climate-economy models: the state of the art

Economy-energy-environmental models have become the standard tool to quantify the economic impacts of climate policy.

Top-down models, being an aggregate representation of the general economy, are more suitable for describing the macro-economic implications of climate and trade policies. They can broadly classified into two types: neoclassical growth

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[4] This framework cannot account for R&D investments that, being profit driven, need a market structure different from perfect competition, as mention in section 2.3.

models and computable general equilibrium (CGE). Growth models solve the economy equilibrium using intertemporal optimization. They can easily be extended to include intertemporal dynamics such as R&D investments, endogenous technological change (ETC) and disembodied spillovers. These models typically have little sectoral disaggregation [5]and therefore they are not very suitable for the study of trade-related issues such as embodied technology spillovers. Instead, computable general equilibrium models (CGEs) are characterized by a detailed sectoral disaggregation of the economic structure of all countries included. Moreover, sectoral trade flows are computed endogenously. Yet, in these multi-sectors models it is more difficult to represent intertemporal dynamics such as investments. There are two ways of specifying long-term dynamics: recursively or intertemporally. Recursive CGE computes static equilibria at each point in time that are then linked in a long run recursive-path by specifying growth dynamics in between time steps (Edenhofer at al., 2005). Dynamic CGEs compute the equilibrium by maximizing the total discount sum of utility and profits over the overall time horizon. In a recursive model future choices will depend on the past, but not the vice versa. A dynamic model is forward-looking and the optimal allocation today depends on future opportunities as well.

CGEs have represented technological progress using different approaches reviewed in Carraro et al. (2002), Jaffe, Newell and Stavins (2002), Weyant and Olavson (1999) and Loschel, (2002). Most CGE models, especially when including a large number of countries and sectors, assume exogenous total factor productivity (TFP) and include an exogenous time-trend in the energy-input coefficient. This parameter, called autonomous improvement in the energy efficiency parameter (AEEI) captures the non-price induced technical change. The justification for a declining energy input coefficient is the stylized fact of falling energy intensity with economic growth and development (Paltsev et al., 2005). A production function with AEEI looks like (Sue Wing, 2005):

$$\begin{aligned} Y(t) &= A(t)F(VA(t), \gamma(t)E(t)) \\ \frac{\partial \gamma(t)/\partial(t)}{\gamma(t)} &= AEEI \leq 0 \end{aligned}$$

where $VA(t)$ is a composite of value-added e.g. labor and capital and $E(t)$ is an energy composite. There has been an increasing interest in the representation of endogenous technological change also in CGE models, using mostly two mechanisms, learning curves and R&D investments and externalities. Goulder and Schneider (1999), in one-country-dynamic CGE model, have introduced an industry that produces R&D services. R&D investments are costly, but at the same time they increase the stock of knowledge and generate a positive externality. A firm benefits from the R&D externality in its industry, which in turns

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[5] In many cases, they produce only one final good. See for example RICE of Nordhaus and Yang, (1996); FEEM-RICE of Bosetti, Carraro and Galeotti (2005); WITCH developed by Bosetti, Carraro,Galeotti, Massetti and Tavoni, (2006).

depends on the industry-wide level of expenditure on R&D. This is an example with ETC in all sectors. Kemfert (2005) has a dynamic CGE model, WIAGEM, where R&D investments directly affect energy productivity. Technical change is induced by climate policies and only cooperating countries invest in R&D. Non-cooperating countries also benefit from the accumulated knowledge capital via spillovers generated by capital flows. DEMETER (Gerlagh et al., 2003) is a dynamic CGE with a bottom up feature in the energy sector. This model has only one region and thus it does not allow for the presence of spillovers across countries. This model introduce ETC via learning curves only in the energy sector, where there are two technologies: fossil fuel-based and carbon free technology. Total production is determined by a nest-CES with two inputs: a capital-labor composite and energy composite. The Hicksian technical progress in the production function and the energy efficient index of the energy composite are exogenous. ETC is implemented by introducing a learning rate in the productivity parameter of the production function of the two energy inputs. The productivity parameter is taken as exogenous by the firm: hence, despite the presence of learning spillovers, firms preserve a constant return to scale production function. Kverndokk at al. (2004) use a two-sectors (electricity and non electricity) dynamic CGE with LBD. They distinguish between traditional and advanced technologies: the latter are more expensive but subject to higher LBD. As in DEMETER ETC is introduced only in the electricity sector.

In principle it would be more appropriate to have ETC in all industries as both energy demanders and suppliers can experience productivity growth and energy efficiency improvements. However, as it emerges from this brief model review, most models have limited the endogenous technological component to the energy sector.

2.5 Accounting for international technology spillovers in a CGE model

Spillovers can take place across technologies, firms, sectors and countries (Sijm, 2004; Weyant and Olavson, 1999). So far modelers have focused on the first three types. Goulder and Schneider (1999) have introduced intra-industry spillovers from R&D. Each firms invests in R&D, contributing to the accumulation of the stock of knowledge that is enjoyed by all firms in a sector. Kverndokk et al. (2004) include sectoral spillovers that stem from LBD. They are confined to the energy sector. Technology diffusion and international spillovers have started receiving increasing attention. Grubb et al. (2002) explore the impact of climate policies under different spillovers scenario and they find that technology diffusion has an impact on CO_2 emissions. However, their study assumes rather than quantifying international technology spillovers. Kemfert (2005) is one of the first attempts to account endogenously for international technology spillovers across countries via capital flows. Buonanno et al. (2001) simulated the presence of international technology spillovers by introducing the stock of world knowledge in the production function and in the emission-output ratio equation. Bosetti, Carraro, Galeotti, Masetti and Tavoni, (2006) have recently introduced disembodied international knowledge spillovers in the optimal growth model WITCH. Gerlagh and Kuik (2006) have analyzed the effect of international technology spillovers on carbon leakage using the GTAP-E CGE model.

The use of a CGE model is more suitable for the study of the geographic and sectoral dimension of technology transfers. Their value-added is the ability of computing trade flows endogenously. In such models endogenous technical change could be driven by endogenous trade flows and international spillovers by trade in specific goods, such as capital goods can be explicitly modeled. They way intra-firms and intra-sectors spillovers have been introduced may provide an example for how to model international spillovers. Next two sections will describe two possible ways of dealing with international technology spillovers in a CGE.

2.5.1 Via learning curves

As illustrated in section 2.4.2, some CGE models have modeled ETC via learning curves, especially in the energy sector. In a CGE, international technology spillovers can be accounted for by linking the learning curves to the trade flows endogenously computed by the model. The major idea behind this approach is that higher trade exposure accelerates the learning process. The empirical evidence supporting this idea is limited to few sectoral studies. Wheeler and Martin, (1992) found that the diffusion of cleaner technologies in the wood pulp industry is positively affected by trade openness. Reppelin-Hill (1999) reached the same conclusions, but in the steel industry. The results are robust to sectoral and aggregate measures of trade openness. It appears that the diffusion of specific technologies is affected not only by the share of sectoral imports, but also by trade exposure in general.

These results could be formalized in a learning curve as follow. Let trade exposure be represented by the variable, TE_t. The idea to be modeled is that higher exposure to trade amplifies the ability and the speed of learning. As illustrated in section 2.3.1, an increase in the inflow of goods, services and investments often leads to the diffusion of technical information and the acquisition of new capacities and notions. The accumulation of new goods and knowledge can increase the learning ability, for example thorough absorptive capacity. For these reasons it might be the case that international technology spillovers also translate into costs reduction.

A suggestion about how actually implementing this idea comes from the traditional learning curve:

$$C_{it} = aCC_{it}^{b} \text{ where } b < 0 \tag{4}$$

The learning rate is defined as the cost reduction that takes place when capacity doubles, keeping everything else constant:

$$LBD = 1 - 2^{b} \text{ rate of learning by doing}$$

This definition of learning rate assumes that all the rest remains constant. However, the relationship between cost reduction and LBD occurs over time: there could be other factors taking place during that period of time that may influence how LBD interacts with costs. For example, changes in trade flows. If during this window of time trade changes, it may affect the relationship between cost reduction and experience accumulation. To account for the contemporaneous change in trade exposure, the learning curve can be extended in the following way:

$$C_{it} = aCC_{it}^{b}TEt^{d} \text{ where } b < 0 \tag{5}$$

A LBD rate accounting for contemporaneous trade influences can be defined as follow:

$$\begin{aligned} 1 - 2^{b}\Delta TEt^{d} \text{ where } \Delta TEt &= TEt + i/TEt \\ if\Delta TEt \leq 1 \text{ then } LR &\leq 1 - 2^{b} \\ if\Delta TEt \geq 1 \text{ then } LR &\geq 1 - 2^{b} \end{aligned}$$

where $i = t + i - t$ is the time interval in which capacity doubles.
The intuition is that greater exposure to trade should benefit the learning process. For example, higher exposure to foreign technologies could affect the learning capacity and thus accelerate the LBD process. In this formulation, trade exposure (e.g. imports of a specific technology) does not play the simple role of additional capacity that adds up to the domestic one, but foreign and domestic capacity are assumed to affect the learning process differently. Foreign capacity may have a different impact because it incorporates a different level of technology. This hypothesis is in line with the condition of gains from trade in the Helpman and Krugman model briefly described at the end of section 2.4.1: the external effect, in this case the learning rate, under free trade should be bigger.

This assumption should be tested empirically. However, as it will be discussed in section 3.2, methods used so far to estimate learning curves does not seem to yield robust results. A production function with endogenous technical change and international spillovers would look like

$$Y_{it} = [\beta CC_{it}^{b}TE_{t}^{d}]F(K_{it}, L_{it}, E_{it})$$

Most CGE climate-models have limited ETC and learning curves to the energy sector, leaving the overall TFP exogenous. Alternatively, learning curves could be introduced also in the other sectors. The use of sector-specific learning curves could account for the heterogeneity of the learning process across sectors, for which there is some empirical evidence (Loschel, 2002). However, the presence of many sectors may makes this attempt cumbersome. Next section will analyze a second approach, which seems more feasible for multi-sector CGE models.

2.5.2 Via productivity and energy efficiency parameters

A more direct way to introduce international technology spillovers is to link the TFP and the AEEI parameters to trade variables. Most CGE models represent the production side of the economy using nested constant elasticity of substitution (CES) technologies with constant return to scale (CRST). This assumption allows to represent the firm's problem by using the dual theory of cost minimization and it allows for biased technological change. Typically at the top nest an energy composite can be substituted for a value-added aggregate. Within both the energy and value-added aggregate further substitution among more specific inputs can occur. The nested structure gives flexibility in allowing for different elasticities between different inputs. The focus here is on the bias toward the energy aggregate as a whole; for this reason the attention is confined to the top nested level, as if there where two aggregate inputs.

A production function accounting for both neutral and biased technological change can be represented using augmenting coefficients:

$$Q = F(\phi_v(t)V_v(t), \phi_e(t)V_e(t)) \tag{6}$$

where $\phi_i(t)$ are the input-specific augmentation factors, V_e is a composite energy input and V_v represent the value-added aggregate. Assuming that $\phi_i(t) = A(t) * \varphi_i(t)$ and that F(.) is homogeneous of degree one in both arguments, the neutral component, the TFP or Hicksian-neutral technical change, can be factored out

$$Q = A(t)F[\varphi_v(t)V_v(t), \varphi_e(t)V_e(t)] \tag{7}$$

Measuring TFP, $\frac{\dot{A(t)}}{A(t)}$, as output over capital and labor adjusted for their share on output, as most of the literature on international spillovers did, is not totally appropriate if the production function includes intermediate or inputs other than labor and capital. A multi-factor productivity measure should be used

$$TFP = dlogQ/dt - (s_v * dlogV_v + s_e * dlogV_e) \text{ where } s_i = P_i * V_i/P_qQ$$

The use of TFP as a measure of productivity and technological change is based on the neoclassical growth theory where this parameter is typically exogenous and it is determined residually as the difference between output growth and the weighted average of factors accumulation. The endogenous growth theory and the theory of endogenous technical change show that important determinants of TFP are the process of innovation and inventions, also denoted as R&D

activities. Several empirical studies find a significant relationship between TFP and several measures of R&D activities (Griliches, 1998; Coe and Helpman, 1995). In this framework another measure of productivity can be derived by the production function used in the endogenous growth theory. Productivity growth can be define as follow: [6]

$$TFP = \frac{\dot{A(t)}}{A(t)} = \frac{\dot{N(t)}}{N(t)} = g * R\&D \tag{8}$$

where R&D can the be R&D expenditure, as in the lab-equipment version of the Romer model (Acemoglu, 2006), R&D employment (Romer, 1990) or the number of blueprints (Grossman and Helpman, 1991). Coe and Helpman (1995) did show that when the R&D sector is a relative small share on GDP, most of the variation in TFP is generated by R&D differences. This measure also has its own drawbacks. Intangible inputs such as knowledge are difficult to measure and are likely to be underestimated by R&D proxies.

Consider a CES specification of equation[7] (7)

$$Q = [\sum(\alpha_i(\phi_i * V_i)^\rho]^{1/\rho}$$

where Q is output, V_i are inputs (in this specific context i= v,e) and $\rho = (\sigma - 1)/\sigma$ with σ the elasticity of substitution between inputs. Cost minimization subject to this production function gives rise to the CES unit cost function

$$C_i(1, P_i) = [\sum(\alpha_i^\sigma (P_i/\phi_i)^{1-\sigma}]^{1/(1-\sigma)}$$

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[6] There are different specifications of endogenous growth theory, but they all share the Dixit-Stiglitz formulation and they all lead to a similar aggregate production function of the form:

$$Y = \frac{N(t)}{1-\beta} K^{1-\beta} L^\beta$$

where N(t) is total number of inputs available and it is growing at a rate g such that

$$N(t) = N(0) * e^{g * R\&D}$$

Under this specification

$$A(t) = \frac{N(t)}{1-\beta}$$

$$TFP = \frac{\dot{A(t)}}{A(t)} = \frac{\dot{N(t)}}{N(t)} = g * R\&D$$

[7] For clarity the time index is omitted. However, prices, augmentation and technology coefficients, inputs and outputs are all time-dependent.

where P_i is the price of input i. Using Shephard's lemma the demand function of each input can be derived

$$\frac{V_i}{Q} = [\alpha_i * \frac{P_q}{P_i} * \phi_i]^{\sigma} \frac{1}{\phi_i} \tag{9}$$

Without loss of generality ϕ_i can be decomposed into the Hicksian neutral technological progress, $A(t)$ and the input-specific bias $\varphi_i(t)$, which in the case of energy is also called AEEI. The unit cost function becomes

$$C_i(1, P_i) = (1/A)[\sum(\alpha_i^{\sigma}(P_i/\varphi_i)^{1-\sigma}]^{1/(1-\sigma)}$$

and the demand function can be expressed as

$$\frac{V_i}{Q} = \frac{1}{A}[\alpha_i * \frac{P_q}{P_i} * \varphi_i]^{\sigma} \frac{1}{\phi_i} \tag{10}$$

Recalling the definition of Binswanger and Ruttan of bias technological change, energy bias is the rate of change in the shares of the energy input over production at constant prices :

$$BIAS = \frac{\partial Se/\partial t}{Se}$$

where $Se = P_e V_e / P_q Q$ is the share of the value of energy input over total costs

$$BIAS = dlog(P_e V_e / P_q Q) \tag{11}$$

Technical change is energy-saving if

$$dlog(P_e V_e / P_q Q) \leq 0$$

or if

$$dlog(V_e/Q) \leq 0$$

controlling for prices.

The structure of technological progress, A, and of the energy bias, φ_e, can be endogenized by turning these two parameters into functions of trade openness, TO. Following Binswanger and Ruttan (1978) and Fisher-Vanden et al. (2004), an exponential form can be assumed:

$$A(t) = \exp(t + TO + ABS) \tag{12}$$

$$\varphi_e(t) = \exp(t + TO + ABS) \tag{13}$$

where t is a time trend, TO represents trade openness and ABS is a variable accounting for the absorptive capacity. The assumption behind these specifications is that TFP and AEEI are determined by the same variables. In other word, the process of technical change is driven by some forces that I am trying to identify. They way it affects each input can differ, generating the notion of biased technical change.

3 Overview of the empirical application of the two approaches

The validity of the two approaches outlined in the previous section should be tested by estimating the impact of trade openness on TFP, AEEI and learning rates. The attention is confined to embodied spillovers and therefore the attention will be on trade in capital goods (equipment and machinery). This section review the existing empirical literature in this field and illustrate the type of econometric analysis required: the actual estimation goes beyond the scope of this paper. The purpose of this section is to investigate the empirical feasibility of both approaches.

3.1 Empirical evidence on international technology spillovers: literature review

The empirical evidence on international technology spillovers has focused on the relationship between total factor productivity (TFP) and:

- Imports in capital goods
- Patent innovations, domestic and foreign R&D
- FDI

Keller (2004) reviews the empirical evidence on all these three types of linkages. Most of the literature has dealt with technological diffusion related to imports (Coe and Helpman, 1995; Coe, Helpman and Hoffmaister, 1997 DeLong and Summers, 1991). Relating TFP to capital import captures the so called embodied knowledge spillovers or indirect benefits. Sue Wing (2005)[8] disaggregate the variable capital goods using two digit level data to study the impact on TFP of different types of capitals. Not all capital categories lead to the same degree of technological diffusion: specialized industrial machinery (72 according to the classification Standard International Trade Classification (SITC), Revision 2) has a stronger impact on TFP compared to the other types of capital.

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[8] This is an unpublished study.

The relationship between TFP and patent or R&D data captures the direct benefit from R&D or disembodied knowledge spillovers (van Meijl, 1995; Coe and Helpman, 1995).

The evidence on FDI is more mixed. Empirical studies on this subject tend to be more country and sector specific, depending on the availability of micro data. One common result is the positive correlation between FDI and firms's productivity. In line with the theoretical prescriptions of the Melitz's model, firms that engage in FDI tend to be more productive. A study on the energy intensity in China found foreign-owned firms to have a lower energy intensity (Fisher-Vandend, Jefferson, Liu and Tao, 2004). Lane and Milesi-Ferretti (1999) show that trade openness and FDI are positive correlated.

So far the empirical literature has focused on the spillovers effects on a neutral measure of productivity, typically total factor productivity (TFP). Less systematic is the empirical evidence on the effect of international technology spillovers on the input bias. Fisher-Vanden et al. (2004), look at the factors that reduced energy intensity in some Chinese industries between 1997-1999. Most of the decline can be explained by a change in the structure of GDP (sectoral shift), R&D firm expenditure and firm ownership. As for the learning curve approach, there are no empirical attempts to quantify the effects of international technology spillovers mediated by trade on the learning process.

3.2 LC approach

The idea is to estimate directly the impact of trade on the learning rate, following the approach developed by Soderholm and Sundqvist (2003). Taking log of the learning curve defined in equation (5) we obtain a linear relation

$$log(C_{it}) = a_i + \beta * log(CC_{it}) + \delta * log(TE_t) + U_{it} \tag{14}$$

from which we can obtain an estimate of the learning index b (β) and of the trade-sensitivity parameter d (δ). This type of relationship has been estimated for specific technologies, such as wind turbine, solar PV cells and panels(McDonald and Schrattenholzer, 2003). Given the ultimate goal of using the estimates in a CGE, an estimation of equation (14) for the all energy sector would be desirable. To this end, data for the all energy sector should be used, such as a proxy of the total unit cost in the energy sector; a measure of total energy installed capacity or installed capacity in respectively clean and carbon technologies should be. Common proxies used for CC_{it} in specific technologies are the cumulative capacity installed, cumulative production or cumulative sales (McDonald and Schrattenholzer, 2000). To define such a measure for the whole energy sector is more difficult: it requires an approximative aggregation of the capacity of all technologies being in use. Kverndokk et al., 2004 measured accumulated experience in the electricity sector with its aggregate accumulated production.

Detailed aggregate data are available at the OECD STAN Bilateral Trade Database. Input-output tables may provide some information about the types of capital imports flowing into the energy sector. Alternatively, capital imports in the energy sector could be approximated by those categories that are known to be used mostly in the energy sector, such as power-generating machinery and equipments (71 according to the SITC classification system). However, the productivity variable in a specific sector such as energy may be affected not just by sectoral but also by aggregate capital imports. Both total and energy-specific capital imports should be tried as independent variables.

Another issue is whether to use trade flows, capital imports at time t, or stock, cumulative capital imports up to time t. The use of trade flows would capture only simultaneous effects, which in a learning process are likely to be small. The use of a stock (or a lag) variable instead would go beyond contemporaneous effects. In a learning process, experience starts exerting its influence with some lag with respect to the time of acquisition. To capture the delayed effects of experience, a stock of cumulative knowledge should be tried.

More specific issues that must be considered are the presence of multicollinearity, as it can be the case that cumulative capacity already includes the capital imported, and the endogeneity of cumulative capacity, as it can be the case that costs also affect capacity accumulation.

Although in principle it would be nice to estimate whether trade openness actually influences LBD occurring in the energy sector, the validity of such results could be reasonably questioned because of the lack of good data. Already troublesome for specific technologies, the estimation of learning curves for a whole sector does not appear to yield robust empirical results.

3.3 TFP approach

The framework developed in section 2.5.2 provides the equations that can be used to estimate the presence and the bias of international technology spillovers. In log terms, equation (12) can be taken to the data:

$$logA_{it} = \beta_1 T + \beta_2 TO_{it} + \beta_3 ABS_{it} + \alpha_i + u_{it} \tag{15}$$

where i is a sector or a country index. This regression focuses on the Hicksian-neutral technical change. From the perspective of climate change what matters is whether technological change and technological spillovers are energy and carbon saving.

Taking the natural log of (10) for $i = e$, an estimable equation for the energy bias can be derived:

$$log\frac{V_e}{Q} = log\frac{1}{A} + \sigma[log\alpha_e + log\frac{P_q}{P_e} + log\varphi_e] - log\varphi_e \tag{16}$$

Plugging the definition for $\varphi_e(t)$ into (18) an estimable equation for energy bias can be obtained

$$log(\frac{V_e}{Q})_{it} = \gamma_0 + \gamma_1 logA_{it} + \gamma_2 log(P_q/P_e)_{it} + \gamma_3 T + \gamma_4 TO_{it} + \gamma_5 ABS_{it} + \beta_i + v_{it} \tag{17}$$

where $\gamma_o = \sigma[log\alpha_e]$. By the definition of energy bias given above, technological progress is energy-saving if $\gamma_3 \leq 0$.

If the production function distinguishes between non carbon and carbon energy inputs, here represented by CO_2 emissions, a similar regression could evaluate whether technical progress is carbon-saving or not:

$$log(\frac{CO_2}{E})_{it} = \beta_0 + \beta_1 logA_{it} + \beta_2 log(P_e/P_c)_{it} + \beta_3 T + \beta_4 TO_{it} + \beta_5 ABS_{it} + \eta_i + \mu_{it} \tag{18}$$

where $\beta_o = \sigma[log\alpha_C]$.

The estimation of these equations will provide a test for the hypothesis of trade as a channel of international technology spillovers that contributed to the process of technological change. If the empirical findings are significant, international technology spillovers can then be modeled by linking the productivity parameter $A(t)$ and the energy-efficiency coefficient $\varphi_e(t)$ directly to trade flows or stocks. Ideally, this should be done at sectoral level, using econometric estimations of the effect of trade variables on sectoral TFP and energy intensity. However, such an analysis could not provide estimates for different countries as sectoral data are not available for a significant number of countries. Therefore, the use of aggregate data would make the estimation phase more straightforward. Most of the data are available in the OECD-IEA statistics and in the World Development Indicators of the World Bank.

Trade openness can be measured by the flow of capital imports from the OECD countries as a total in US\$ dollar.[9] Capital goods are carriers of the knowledge they embodied and thus it seems reasonable to think about technologically sophisticated goods as a channel for international transmission, as illustrated in section 2.3.1. Since technological spillovers may take time to exert any effect both lag and cumulative imports should be tried as independent variables. Different types of capital goods will be used. Machinery and equipment (ISIC - REV 3, 29-33), machinery and equipment n.e.c. (ISIC - REV 3, 29), electrical machinery and apparatus (ISIC - REV 3, 31), motor vehicles, trailers and semi-trailers (ISIC - REV 3, 34) and other transport equipment (ISIC - REV 3, 35). Equation (15) only accounts for spillovers that occurs indirectly trough trade (also called indirect or embodied spillovers). This channel could interact with the level of R&D activities in the exporting countries, in this case the OECD countries: to capture this effect a further term $Mjt * R\&D_{oecd}$

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[9] The decision of focusing only on OECD exports of capital goods is due to the fact that R&D activities are concentrated in these countries. Spillovers are expected to be generated by the most innovating countries.

is included. Higher R&D in machinery and equipments should lead to bigger spillovers. The OECD STAN industry dataset contains R&D expenditure in OECD countries by sector, allowing the possibility of interacting each type of capital good with its R&D expenditure share.

Human capital should be included as a measure of the absorptive capacity of a country. It seems that the measure of human capital that is most correlated with growth is the net secondary school enrollment ratio of male. However, these type of data are available up to 1999 (Barro&Lee database) and on a five-year base. The World Development Indicators have more recent data, up to 2002, but not homogeneously for all countries. Better data are available for the gross secondary school enrollment ratio. Another variable that can be used to account for higher level education is the number of scientific and technical journal articles.

Two measures of energy intensity can be used: aggregate energy intensity (measured in thousand of tonnes of oil equivalent (Ktoe) per PPP international US dollars of GDP) and per capita energy intensity (kilogram of oil equivalent (Kgoe) per PPP international US dollars of GDP). Energy use is measured as total final consumption of the total of all energy sources. The term final consumption (equal to the sum of end-use sectors' consumption) implies that energy used for transformation and for own use of the energy producing industries is excluded. Final consumption reflects for the most part deliveries to industry and the energy use in the transportation sector.

Data on energy prices are by type of product. Ideally it would be preferable to have an index for the real end use energy price, but such a measure is available only for OECD countries. For the non OECD countries, a weighted average price should be constructed. Another option could be to include the world oil price, which probably plays a significant role but would not explain any cross-country variation.

Energy intensity is related to the structure of an economy: the larger the share of energy-intensive activities, the bigger this ratio. Changes in sectoral composition of total output should be controlled for. The World Development indicators contains data on the percentage of GDP produced by different sectors (agriculture, industry, manufacturing, services).

As mentioned above a measure of multi-factor productivity accounting for the presence of energy inputs should be used. However, the measurement of the energy share can be problematic as it requires data on energy prices. Moreover, this share is likely to vary over time. Alternatively, following the endogenous growth theory approach outlined above, the productivity parameter $A(t)$ can be approximated by a R&D variable. The stock of real expenditure, the number of patents (both for residents and non residents) and the number of workers in the R&D sector will be tried.

Such an econometric analysis would provide the effects of imports on TFP, which is an aggregate measure of technical progress. It includes fast-growing sectors as well slow-growing sectors. To be integrated in a CGE model this aggregate elasticity needs to be converted into the sectoral parameters, using some factors of conversion such as value-added based productivity measures that reflect an industry capacity to contribute to economic-wide growth (OECD, 2001).

4 Conclusions

This paper explores the issue of integrating international technology spillovers in a climate CGE model. More precisely, it looks at the spillovers embodied in capital goods and that are therefore driven by trade in such goods. Given the two major mechanisms used to model technological change, two approaches could potentially be conceived: a first approach relying on learning curves and a second one aimed at linking TFP and AEEI with trade. Although in theoretical terms both approaches are possible, when turning to the empirical estimation of the key parameters, the second approach seems more straightforward. The estimation of learning curves accounting for the contemporaneous change in trade exposure is too demanding in terms of data. Moreover, learning curves are more appropriate for specific technologies than for entire sectors. Given these conclusions, the next research step is to estimates the relationship between TFP, AEEI and measures of trade openness. This estimation would provide a test for the hypothesis of trade as a channel of embodied international technology spillovers. If the empirical findings are significant, international technology spillovers can then be modeled by linking the productivity parameter $A(t)$ and the energy-efficiency coefficient $\varphi_e(t)$ directly to trade flows or stocks.

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A Technical change and biases: three definitions

A production function accounting for both neutral and biased technological change can be represented using augmenting coefficients or inputs expressed in the per effective unit. Using augmentation coefficients:

$$Q = F(\phi_v(t)V_v(t), \phi_e(t)V_e(t)) \tag{19}$$

where $\phi_i(t)$ are the input-specific augmentation factors, V_e is a composite energy input and V_v represent the value-added aggregate. Assuming that $\phi_i(t) = A(t)* \varphi_i(t)$ and that F(.) is homogeneous of degree one in both arguments, the neutral component, the TFP or Hicksian-neutral technological change, can be factored out

$$Q = A(t)F(\varphi_v(t)V_v(t), \varphi_e(t)V_e(t))$$

At constant prices technical biases is defined as (Kamien and Schwartz, 1969)

$$\frac{\dot{V_v(t)}}{V_v(t)} - \frac{\dot{V_e(t)}}{V_e(t)} = dlog(V_v(t)/V_e(t)) = (1-\sigma)[\frac{\dot{\varphi_e(t)}}{\varphi_e(t)} - \frac{\dot{\varphi_v(t)}}{\varphi_v(t)}]$$

where σ is the elasticity of substitution between the two composite inputs. For low values of σ, $\sigma < 1$

$$\begin{cases} dlog(V_v(t)/V_e(t)) \geq 0 & \text{E-saving} \\ dlog(V_v(t)/V_e(t)) \leq 0 & \text{E-using} \end{cases}$$

The intuition is that if technical progress affects the augmentation of an input more than proportionally, it reduces the effective amount needed for producing a certain quantity of output.
Let us assume that $\varphi_v(t) = 1$ so that $\frac{\dot{V_v(t)}}{V_v(t)} = \frac{\dot{A(t)}}{A(t)} = TFP$

$$Q = AF(V_v(t), \varphi_e(t)V_e(t))$$

In this case the energy bias can be defined as: $TFP - AEEI$, where

$$AEEI = \frac{\dot{\varphi_e(t)}}{\varphi_e(t)}$$

Technical change is energy-saving if $TFP - AEEI \leq 0$.

The other way of including technical change in the production function is using effective inputs:

$$Q = F(\phi_v(t)V_v(t), \phi_e(t)V_e(t)) \tag{20}$$

where $\phi_i(t)$ are the input-specific augmentation factors, V_e is a composite energy input and V_v represent the value-added aggregate. Assuming that $\phi_i(t) = A(t)/\gamma_i(t)$, the production function can be expressed in effective inputs and Hicksian-neutral technical change can be factored out:

$$Q = A(t)F(V_v(t)/\gamma_v(t), V_e(t)/\gamma_(t))$$

At constant prices technical biases is defined as (Kamien and Schwartz, 1969)

$$\frac{\dot{V_v}(t)}{V_v(t)} - \frac{\dot{V_e}(t)}{V_e(t)} = (1-\sigma)[\frac{\dot{\gamma_v}}{\gamma_v} - \frac{\dot{\gamma_e}}{\gamma_e}]$$

where σ is the elasticity of substitution between the two composite inputs. For low values of σ, $\sigma < 1$

$$\begin{cases} (1-\sigma)[\frac{\dot{\gamma_v}(t)}{\gamma_v(t)} - \frac{\dot{\gamma_e}(t)}{\gamma_e(t)}] \geq 0 & \text{E-saving} \\ (1-\sigma)[\frac{\dot{\gamma_v}(t)}{\gamma_v(t)} - \frac{\dot{\gamma_e}(t)}{\gamma_e(t)}] \leq 0 & \text{E-using} \end{cases}$$

The lower $\gamma_i(t)$, the higher the output for a given level of input $V_i(t)$. If $\gamma_v(t)$ is growing at a lower rate than $\gamma_e(t)$, it means that to produce the same output we need a lower quantity of $V_v(t)$ relative to $V_e(t)$. In the factor augmentation expression technological progress enter multiplicatively meaning that the higher the augmentation coefficient, the higher the output for a given level of inputs.

The two definitions are equivalents because

$$\varphi_i = \frac{1}{\gamma_i}$$

which implies that

$$\frac{\dot{\varphi_i}(t)}{\varphi_i(t)} = -\frac{\dot{\gamma_i}(t)}{\gamma_i(t)}$$

$$(1-\sigma)[\frac{\dot{\gamma_v}(t)}{\gamma_v(t)} - \frac{\dot{\gamma_e}(t)}{\gamma_e(t)}] = (1-\sigma)[\frac{\dot{\varphi_e}(t)}{\varphi_e(t)} - \frac{\dot{\varphi_v}(t)}{\varphi_v(t)}]$$

When there are more than two inputs, a measure of bias that accounts for factor prices is the rate of change in the factor share, where the factor share is defined as the value of an input over total costs (Binswanger and Ruttan, 1978):

$Si(t) = Pi(t)Vi(t)/P(t)Q(t)$
biases $= \dot{Si}(t)/Si(t) = \widehat{Pi} + \widehat{Vi} - \widehat{P} - \widehat{Q} = dlog(Vi(t)/Q(t)) - dlog(P(t)/Pi(t))$

$$\begin{cases} \dot{Si(t)}/Si(t) \geq 0 & \text{i-using} \\ \dot{Si(t)}/Si(t) \leq 0 & \text{i-saving} \\ \dot{Si(t)}/Si(t) = 0 & \text{i-neutral} \end{cases}$$

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