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Technology diffusion under contraction and convergence: A CGE analysis of China

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ABSTRACT

This paper introduces a mechanism of international technology diffusion via FDI and imports into recursive-dynamic CGE modeling for climate policy analysis. As a novel feature, the mechanism distinguishes spillovers from foreign do domestic capital within sectors and across sectors within the production chain. The paper applies the mechanism to the analysis of a contraction and convergence type climate policy focusing on China. The mechanism of international technology diffusion leads to an increase in China's energy productivity an a decline in China's economic growth rates in a convergence process. In this case, inter-regional emissions trading could (more than) compensate China's welfare losses due to climate policy. Otherwise, China's welfare losses due to climate policy could be significant.

1. Introduction

The Chinese economy is expected to keep on growing and to stay the world's main emitter of greenhouse gases, since it strongly relies on carbon intensive coal as an energy source. In 2004 China's carbon intensity[1] was more than three time that of Germany (World Bank, 2008b). According to IEA (2007) projections, China's energy demand will more than double between 2005 and 2030, and China will be the world's biggest energy consumer soon after 2010. China therefore plays a key role within an international climate policy regime in order to prevent at least the most severe impacts of climate change. A Chinese commitment to reduce emissions would encourage the USA and developing countries to make commitments on emissions reductions as well. In this context, a per capita emissions based contraction and convergence regime (GCI, 1990) has a realistic chance of being accepted by countries with currently low per capita emissions such as China. It can even be beneficial for developing countries due to revenues from selling excess emissions permits.

China is highly integrated into the world economy. It is worldwide one of the largest recipients of foreign direct investment (FDI) and plays a central role in global commodity trade. And China's global economic integration strongly affects its growth and thus also the resulting environmental impacts. At the same time, economic integration promises an opportunity that is currently frequently present in the political debate as well as in the literature: international technology diffusion (e.g. summarized by IPCC, 2000; OECD, 2002; World Bank, 2008a). Besides other channels, international technology diffusion can occur through trade and FDI, which are the focus of this paper.

Technology diffusion can be a key to improve the energy efficiency of production and private consumption and to decarbonise energy generation. But the right gateways for applying the key have not yet been clearly identified. A better theoretical and quantitative understanding of the economic effects and the underlying economic interactions is essential for opening up and supporting the right channels of technology diffusion. In the words of Popp (2006): "Diffusion of energy technologies, particularly across countries, is a fruitful avenue for further research." A better understanding of international technology diffusion could also ease China's decision on joining an international climate policy negotiation.

Approaches for modeling endogenous technological progress within regions are common in the climate policy modeling literature (for overviews see Weyant and Olavson, 1999; Grubb et al., 2002;

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[1] Carbon intensity measured as CO_2 emissions in kg per 2005-PPP-Dollar of GDP.

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Löschel, 2002; Köhler et al., 2006). Technology diffusion across regions is sometimes modeled with the help of a global knowledge stock (for instance Buonanno et al., 2003). There are also some CGE models in the field of development economics that take technology spillovers via FDI and trade into account (van Meijl and van Tongeren, 1999; Diao et al., 2005, 2006). Furthermore, Bosetti et al. (2008) implement international technology spillovers in the endogenous growth model WITCH. They combine the principles distance to technology frontier, knowledge pool and absorptive capacity. Leimbach and Edenhofer (2007) and Leimbach and Eisenack (2009) develop algorithms similar to Negishi (1972) that can handle trade induced technology spillovers in growth models. Leimbach and Baumstark (2010) model international technology spillovers coupled with bilateral trade flows in a growth model. But despite the importance of international technology diffusion in the context of emissions savings, there seems to be a lack of multi-region, multi-sector CGE models for climate policy analysis that take international technology diffusion via FDI and trade explicitly into account (c.f. De Cian, 2006 for a review of possibilities of modeling international technology spillovers in CGE models). Leaving out international technology diffusion can lead to an underestimation of policies that affect FDI and trade.

This paper fills this gap by introducing a mechanism of international technology diffusion via FDI and trade into CGE modeling for climate policy analysis. Herein, the diffusion mechanism and the calibration are closely related to the broad empirical literature on technology diffusion via FDI and trade. A sectoral CGE model including technology diffusion is able to estimate the overall effect of FDI and trade on output and emissions consisting of the scale effect (output expansion), the composition effect (sectoral changes) and the technique effect (productivity improvements, c.f. Antweiler et al., 2001).

First, it is a contribution of the paper to model FDI explicitly, which is not a standard feature in CGE modeling and not covered by the GTAP data. For this purpose, we calibrate FDI inflows into China to data from the China Statistical Yearbook. Second, it is a contribution of the paper to extend the existing mechanisms of modeling international technology diffusion by distinguishing horizontal spillovers (within sectors) and vertical spillovers (between sectors in the production chain). Third, it is a contribution of the paper to transfer the mechanism from general technology diffusion to energy specific technology diffusion.

Since the inclusion of China is a key step for climate policy, research into this issue crucial. IEA (2007) provides recent comprehensive descriptions and projections of Chinese energy issues until 2030. Accordingly, Chinese energy policy can cut China's primary energy use in 2030 by about 15% compared with the reference scenario. Moreover, a number of authors examine the effects of emissions cuts on the Chinese economy with the help of numerical models (e.g. Zhang, 1998; Garbaccio et al., 1998; Wu et al., 2004; Blanford et al., 2008 with MERGE). Nevertheless, further research is needed to figure out how to include China in recently discussed post-Kyoto policies. Therefore, we apply our diffusion mechanism to the analysis of a contraction and convergence type climate policy that starts in 2020 and leads to equal per capita emissions of 2t of CO_2 in 2050. This policy aims at reaching the 2° target as emphasized at Copenhagen 2009. A new insight is that fostering energy saving technology diffusion in combination with a per capita based distribution of emissions permits and permit trade could more than compensate mainland China's welfare losses due to emissions cuts and thus be beneficial for China. Even in the absence of energy saving technology diffusion, permit trade could compensate mainland China's welfare losses due emissions cuts. In both cases it is a precondition that China's economic growth rates decline over time in a log-run convergence process. If China can sustain high economic growth, accumulated, discounted welfare losses might rise to around 4%. These insights are the fourth and main policy relevant contribution of the paper.

The paper is structured as follows: Section 2 gives an overview of the underlying version of the DART model. Section 3 defines technology scenarios. Section 4 describes how international capital movements representing FDI are modeled. Section 5 explains the methodology of implementing general technology diffusion through FDI and trade, while section 6 transfers this methodology to energy specific technology diffusion. Section 7 examines the welfare effects of a contraction and convergence type climate policy. Section 8 concludes.

2. Overview of the DART model

The DART (Dynamic Applied Regional Trade) model is a multi-region, multi-sector recursive dynamic CGE model of the world economy. For a detailed description see Springer (2002) and Klepper et al. (2003). The version of the model scrutinized here[2] distinguishes three regions: mainland China (*CHI*), industrialized region (*IND*) and developing region (*DEV*). The industrialized region encompasses the OECD countries plus Hong Kong (China), Macao (China), Taiwan (China) and Singapore. The latter are included here, since they are important sources of FDI to mainland China (compare Tseng and Zebregs, 2002; Whalley and Xin, 2006). All other countries are named developing countries. The current sectoral aggregation covers 30 sectors in each region.[3] The model distinguishes four production factors: labor, capital and land and natural resources (fossil fuels). In order to analyze climate policies, CO_2 emissions are calculated based on the carbon content of the fossil fuels coal, gas and oil burned in final or intermediate production or consumption.

We assume perfect commodity and factor markets. In each region, there is one representative consumer who incorporates private and public consumption, and one representative producer for each sector. Producer behavior is derived from cost minimization for a given output. The final consumer receives all income generated by providing primary factors for production. A fixed share of income is saved, while the remaining income is used for purchasing commodities. Herein, the expenditure function is modeled as a composite of an energy aggregate and a non-energy aggregate.

Labor is a homogenous good, mobile across industries within regions, but immobile across regions. While in the basic version of the DART model capital is also internationally immobile, in this version capital can be transferred from the industrialized region to China (see section 4). All regions are linked by bidirectional trade flows of all commodities except the investment good. Domestic and foreign commodities are imperfect (Armington) substitutes distinguished by the country of origin.

The DART model is recursive-dynamic. It solves for a sequence of static one-period equilibria for future time periods. The major exogenous, regionally different driving factors of the model dynamics are population growth, total factor productivity growth, human capital growth and capital accumulation. Herein, this version of the DART model includes endogenous international technology diffusion (see Sections 5 and 6). Population growth rates and labor

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[2] For the full mathematical description see the supplementary material.

[3] Agriculture and food (AGR), beverages and tobacco (BEV), business services (BUI), chemicals, rubber and plastic (CRP), culture and recreation (CUS), coal extraction (COL), communication (COM), construction (CON), crude oil extraction (CRU), electrical equipment (ELM), electricity (ELE), ferrous metals (FEM), financial intermediation (FIN), gas extraction (GAS), machinery (MAC), metal products (MET), minerals (MIN), non-ferrous metals (NFM), non-metallic mineral products (NMM), other manufacturing (OTM), paper products and publishing (PAP), petroleum and coal products (OIL), public services (PUB), real estate (REE), textile, apparel and leather (TEX), trade and wholesale (TRD), transport machinery (TRM), transportation (TRN), water supply (WAT), wood (WOO). (Garbaccio et al., 1998 distinguish 29 sectors of the Chinese economy.)

participation rates are taken from the PHOENIX model (Hilderink, 2000) in line with recent OECD projections. Growth rates of human capital are taken from Hall and Jones (1999).

The static part of the DART-Model is currently calibrated to the GTAP 7 database (Narayanan and Walmsley, 2008) for the benchmark year 2004. The model runs under GAMS MPS/GE.

3. Technology scenarios

Because of the uncertainty of future technological progress, we define three technology scenarios:

In scenario *blue,* we consider *general* endogenous technology diffusion into China additional to exogenous general technological progress (see Section 5). We do not consider energy specific technological progress in any region. China's resulting GDP and CO_2 emissions follow projections by OECD (2008) and the *Reference Policy Scenario* by IEA (2007). It is crucial that the theoretical approach for technology diffusion leads to a convergence process: China's labor productivity comes closer to that of the industrialized region, while the growth rate of labor productivity steadily decreases. This scenario is slightly pessimistic with respect to energy efficiency improvements.

In scenario *green,* we add exogenous and endogenous energy specific technological progress to general technological progress given by scenario *blue* (see Section 6). China's resulting CO_2 emissions follow the *Alternative Policy Scenario* by IEA (2007). Again, China's labor productivity as well as energy productivity follow a convergence process towards the industrialized region with declining growth rates over time. This scenario is optimistic with respect to energy efficiency improvements, especially in China.

In scenario *brown,* we consider only exogenous general technological progress in China. Importantly, China's short-run growth rates are lower than in the other scenarios, but its long-run growths rates are higher. China's resulting CO_2 emissions follow the *High Growth Scenario* by IEA (2007). This scenario is rather pessimistic with respect to energy efficiency improvements.

4. International capital mobility

This section describes the modified production structure including international capital mobility for representing FDI. International mobility of capital or savings is not a standard feature in CGE models. It is implemented in a number of models in different ways, though (e.g. Hertel and Tsigas, 1997 in GTAP, Bchir et al., 2002 in MIRAGE, Mai 2004 in PRCGEM for China, van der Mensbrugghe, 2005 in LINKAGE). The methodology used here follows the CES (constant elasticity of substitution) portfolio approach by Goulder and Eichengreen (1989), first applied to the DART model by Springer (2002). The mechanism works in a similar way as Armington trade.

4.1. Methodology

In the DART model, capital[4] accumulates based on the standard Solow–Swan model with a fixed savings rate. Regional investments equal to savings increase the regional capital endowments across periods. Investments are produced in form of an investment good, which requires production factors as inputs as any other kind of production. Within regions *R*, capital is perfectly mobile across sectors. Additionally, in this version of the DART model, capital can be transferred from the industrialized region (*IND*) to mainland China (*CHI*). On the contrary, capital is assumed to be immobile between the other regions. We make this assumption because most of FDI to mainland China stems from the industrialized countries and from Hong Kong (China), Macao (China), Taiwan (China) and Singapore, that are also included in *IND* (c.f. Tseng and Zebregs, 2002; Whalley and Xin, 2006).

In *IND* the supply of capital (services) is diverted into domestic use and foreign direct investment to *CHI* via a CET (constant elasticity of transformation) function with an elasticity ε_{KIND}. The return on foreign direct investment is received by the representative consumer of *IND*.

Fig. 1 shows the main production structure in China, which is the same in *IND* and *DEV* except the foreign capital input, i.e. there is only one kind of capital used in production in *IND* and *DEV*. The production structure principally follows the MIT EPPA model described by Paltsev et al. (2005).[5] The lower right nest combines the production factors capital, labor and energy. In China capital consists of foreign capital originating from *IND* and domestic capital combined with an elasticity of substitution ε_{KCHI}. Foreign and Chinese capital basically differ in terms of embodied technologies. The higher ε_{KCHI} the more equal are both kinds of capital. In the next level the capital-labor-energy composite is combined with land with a low elasticity of substitution. This represents land as a scarce factor. The capital–labor–energy–land-composite is then combined with an intermediate input aggregate in form of a Leontief function. A CET function finally diverts output into the domestically sold and the exported part, given an elasticity of transformation τ.

4.2. Calibration

The GTAP 7 data do not contain benchmark quantities of *foreign* capital. Hence, the benchmark quantities of foreign capital are derived from the China Statistical Yearbook (2006, 2007). The total value of foreign capital in *CHI* originating from *IND* is computed as:

$$K_{IND,CHI} = \kappa_{IND,CHI} K_{CHI} \tag{1}$$

$\kappa_{IND,CHI}$ is the total share of foreign capital relative to *all* foreign capital in China in the benchmark year, namely 9.7%. $\kappa_{IND,CHI}$ is approximated by the sum of total investment in fixed assets by foreign funded economic units and by economic units with funds from Hong Kong, Macao and Taiwan divided by total investment in fixed assets.[6] The underlying assumption is that capital investment shares are a good approximation for capital stocks (given a time invariant investment share $\kappa_{IND,CHI}$). K_{CHI} is the benchmark value of all capital in China given by the GTAP 7 data. This value is used for calibrating the CET function of capital service supply in *IND*. This value is also subtracted from the capital account surplus in *IND* and added to the capital account surplus in *CHI*. This implies that a certain part of the capital account in each region is now explicitly treated as returns from FDI.

In the next step $K_{IND,CHI}$ is distributed across Chinese sectors *i* based on the benchmark sectoral shares of foreign capital κ^{i}_{SEC}:

$$K^{i}_{IND,CHI} = \kappa^{i}_{SEC} \kappa_{IND,CHI} K_{CHI} \tag{2}$$

κ^{i}_{SEC} is the share of foreign capital in sector *i* in *all foreign* capital in China.[7] We approximate the foreign capital shares of the sectors agriculture, manufacturing, construction etc. by inter-sectoral shares of actually utilized investment values. Within the industrial sector, the foreign capital shares (for manufacture of transport equipment etc.)

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[4] The DART model uses values of capital *services* for calibration and calculation. This implies a multiplication of all capital stock values by a constant factor, i.e. a constant scaling of all capital values in the model (stock to flow conversion). For simplicity, we use the term “capital” instead of “capital services” throughout the paper.

[5] The nest structure is simplified compared to the original DART model so that the solver can handle the more complex model including technology diffusion.

[6] Due to restricted data availability on investment in fixed assets for 2004, the *share* of foreign investment in total investment is computed as an average value over the years 2005 and 2006.

[7] The sectoral data in the China Statistical Yearbook are aggregated in order to match the GTAP data. Due to restricted data availability on investment in fixed assets for 2004, the *shares* of foreign capital in specific sectors relative to all foreign capital in China are computed as averages over the years 2005 and 2006.

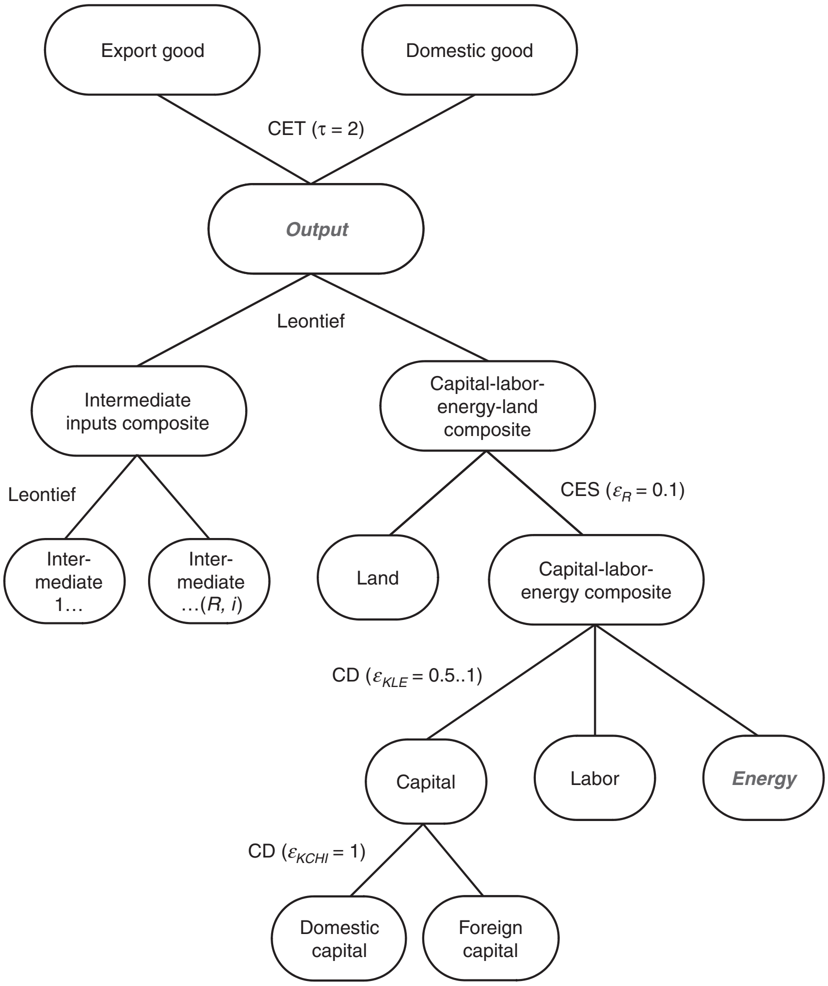

Fig. 1. Main production structure (the foreign capital input appears in *CHI* , but not in *IND* and *DEV,* elements affected by technology diffusion are written in bold letters).

are given by inter-sectoral shares of *total assets* of enterprises with Hong Kong, Macao, Taiwan and foreign funds.[8]

In the CET function that splits capital *IND*, ε_{KIND} is set to two. Thus, capital assets at home or in China are imperfect, but relatively good substitutes. ε_{KLE}, the elasticity of substitution between capital, labor and energy, is set to one, which is the standard Cobb–Douglas form (c.f. Popp, 2006).[9] This implies a relatively good substitutability of production factors, e.g. of energy when imposing a carbon price. In a sensitivity analysis, we will reduce ε_{KLE} to 0.5. ε_{KCHI} is also set to one. Therefore, foreign and domestic capital are not perfect substitutes in Chinese production. This difference between domestic and foreign capital is explained by the difference in embodied technologies.

Table A1 in the Appendix gives an overview of sectoral indicators for China in the benchmark situation derived from the GTAP 7 data.

5. General productivity gains via FDI and imports

FDI directly improves productivity in the destination country when the foreign-owned firms are more productive than the domestic firms. FDI indirectly creates productivity spillovers to local firms via product and process imitation (like reverse engineering) and demonstration effects (like on the job training and adoption of management skills) or via the exchange of employees (workers, technicians, managers), via horizontal spillovers (within sectors) and vertical linkages (between sectors within the production change) (cf. Saggi, 2002). Imports of investment goods (such as machinery) indirectly create productivity spillovers via imitation of the imported goods and via improved application methods adopted together with the imported goods. Moreover, both FDI and trade potentially lead to productivity gains via stronger competition for domestic firms due to the presence of productive foreign-owned firms and rivalling imports.

A broad strand of the empirical literature, covering country case studies and cross section and panel estimations, examines such productivity gains and growth effects of trade and FDI - with mixed results (for overviews see Branstetter, 1998; Kokko, 1992; Saggi, 2002; OECD, 2002; Keller, 2004; World Bank, 2008a).

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[8] FDI inflow data reported by the National Bureau of Statistics China can differ from FDI figures reported by individual investing countries. Moreover, so-called round-tripping capital, originating from Mainland China and returning through Hong Kong possibly accounts for up to 20% of foreign capital (Dees, 1998). And overall round-tripping capital possibly accounts for up to 40% (Xiao, 2004). This insight contradicts expectations of large technology spillovers associated with capital imports. On the other hand, Whalley and Xin (2006) explain that the share of wholly foreign-owned enterprises (instead of foreign-domestic joint venture enterprises) increased between 2000 and 2004 from 46.9% of accumulated FDI to 66% which may accelerate technology diffusion. The reason is that multinational enterprises are likely reluctant to transfer their most advanced technologies to joint venture affiliates, because they fear to reveal their technology based competitive advantages to rivals. Finally, economic activities are unevenly distributed across China, most economic activities taking place in the Eastern costal region (c.f. Groenewold et al., 2008). Nevertheless, taking round-tripping capital and the spatial dimension of technological progress and spillovers within China into account is beyond the scope of our CGE analysis.

[9] Böhringer and Welsch (2004) raise the elasticity of substitution between the energy and the non-energy composite from 0.2 in 2000 (short-run value) to one in 2050 (long-run value).

5.1. Methodology

The following implementation of general productivity gains via FDI and imports based on the Gerschenkron effect combines elements from the classic distance to (technology) frontier approach by Nelson and Phelps (1966) and by Findlay (1978) who includes foreign capital.[10] Acemoglu (2009) and Aghion and Howitt (2009) provide recent theoretical descriptions of the distance to frontier approach. Hübler (2010) analyses the theoretical properties of the basic mechanism used here (without sectoral effects). The distance to frontier approach basically creates technological catching up of the technology follower, in this case *CHI*, towards the technology leader, in this case *IND*, in a convergence process (for empirical background information with respect to China see Young and Lan, 1997).

Similar diffusion mechanisms are used in CGE models for trade and development analyses by van Meijl and van Tongeren (1999, GTAP); Diao et al. (2005, 2006), and in the growth models examined by Leimbach and Edenhofer (2007), Leimbach and Eisenack (2009) and Leimbach and Baumstark (2010).

Additionally, we take forward and backward spillovers across industries explicitly into account, motivated by the empirical literature (c.f. Javorcik, 2004, referring to China see Liu, 2002, 2008).[11]

The following function relates the relative change in total factor productivity (in other words the rate of technological progress) $\Delta A^{it}_{CHI}/A^{it}_{CHI}$ in a certain Chinese sector i in year t to the foreign capital and import shares in that sector and year and to vertical linkages to other sectors.[12] This leads ceteris paribus to an increased output value in the production structure in Fig. 1.

$$\frac{\Delta A^{it}_{CHI}}{A^{it}_{CHI}} = \phi^{t}_{CHI}\mu_{CHI} \cdot \left(\mu_K \frac{K^{it}_{IND}}{K^{it}_{CHI}} + \mu_M \frac{M^{it}_{IND}}{Y^{it}_{CHI}} + \mu_B \sum_{b;b\neq i} \frac{K^{bt}_{IND}}{K^{bt}_{CHI}} \frac{D^{ibt}_{CHI}}{Y^{it}_{CHI}} + \mu_F \sum_{f;f\neq i} \frac{K^{ft}_{IND}}{K^{ft}_{CHI}} \frac{D^{fit}_{CHI}}{Y^{it}_{CHI}}\right) \cdot \left(\frac{\frac{Y^{it}_{IND}}{L^{it}_{IND}}}{\frac{Y^{it}_{CHI}}{L^{it}_{CHI}}} - 1\right) + a_{CHI} \tag{3}$$

ϕ^{t}_{CHI} is the human capital level in China that is shown to influence productivity spillovers in China by Lai et al. (2006) and Xu and Wang (2000), but questioned by Wei (1993). Its multiplicative interaction with the sources of growth is motivated by the use of interaction terms in the econometric literature (e.g. Lai et al., 2006). The human capital level improves over time exogenously in the different regions. Total factor productivity a_{CHI} increases exogenously as well (based on Hall and Jones, 1999). Total factor productivity is the only source of technological progress in the regions *IND* and *DEV* since technology diffusion is modeled only in China. $K^{it}_{IND}/K^{it}_{CHI}$ denotes the share of foreign capital originating from *IND* relative to Chinese capital in each sector. $Y^{it}_{IND}/L^{it}_{IND}$ divided by $Y^{it}_{CHI}/L^{it}_{CHI}$ is the relative difference in labor productivities (output value divided by the labor force size) between *IND* and *CHI* in each sector, representing the gap between the technologies in practise.[13] Since sectoral labor inputs L^{it}_{R} in form of the number of workers are not directly given by the GTAP 7 data, we compute them in the following way:

$$L^{it}_{R} = \frac{l^{it}_{R}}{l^{total,t}_{R}} L^{total,t}_{R} \tag{4}$$

$l^{it}_{R}/l^{total,t}_{R}$ denotes the labor input value in sector i relative to the total labor input value in region $R = \{CHI, IND, DEV\}$ at time t. $L^{total,t}_{R}$ is the size of the total labor force in that region at time t. In other words, the equation expresses the number of workers in a sector L^{it}_{R} as the labor input value in that sector l^{it}_{R}, divided by the average wage $l^{total,t}_{R}/L^{total,t}_{R}$ in region R.

μ_{CHI} is a constant parameter that determines the general spillover strength in China. μ_K is the spillover strength with respect to foreign capital relative to μ_{CHI} which is normalized to 1. Then μ_M is the spillover strength stemming from imports relative to the import strength stemming from foreign capital. Technology diffusion associated with μ_K and μ_M describes *horizontal* technology spillovers within a sector i. Technology diffusion associated with μ_B and μ_F describes *vertical* technology spillovers between sectors in the production chain. μ_B is the spillover strength with respect to backward linkages through intermediate goods supplies, and μ_F with respect to forward linkages through intermediate goods inputs. Herein, backward linkages indicate "contacts between domestic suppliers of intermediate inputs and their multinational clients" (Javorcik, 2004) and appear as the most important spillover channel. $M^{it}_{IND}/Y^{it}_{CHI}$ describes the import value to output value ratio in each sector. This implies that only newly imported commodities bring about additional knowledge. $K^{bt}_{IND}/K^{bt}_{CHI}$ denotes the foreign capital share in a downstream sector b. $D^{ibt}_{CHI}/Y^{it}_{CHI}$ is the value of intermediate goods transferred from sector i to sector b divided by the output value of sector i. In the same way, $K^{ft}_{IND}/K^{ft}_{CHI}$ denotes the foreign capital share in an upstream sector. $D^{fit}_{CHI}/Y^{it}_{CHI}$ is the value of intermediate goods transferred from sector f to sector i divided by the output value of sector i. Summing up over all upstream and downstream sectors captures all inter-sectoral vertical spillovers.

In summary, A, K, D, M, L and Y are endogenous variables; φ increases exogenously; and the μ parameters and a are exogenous parameters that we need to calibrate.

5.2. Calibration

We calibrate the model in four basic steps.

(1) The general literature on productivity spillovers finds elasticities of total factor productivity (or output) with respect to FDI (or intensities of FDI inflows or FDI equity shares) and imports (or import intensities) in the range of 0.03 to 0.1, many elasticities being around 0.05.[14] Furthermore, many econometric studies specifically examine the Chinese economy and find elasticities in a similar range.[15] Like studies about other countries (c.f. Javorcik, 2004), studies about China identify backward linkages as the most significant spillover channel (c.f. Liu, 2002, 2008).[16] Technology diffusion through FDI seems to

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[10] For a related prominent empirical contribution using data for Venezuela see Aitken and Harrison (1999).

[11] For an implementation of inter-sectoral R&D spillovers see Lejour et al. (2006).

[12] Such a technology diffusion based convergence mechanism is supported by empirical evidence. For instance, World Bank (2008b) data describe that the spread of personal computers, of internet access and of broadband subscriptions in China increased strongly after the introduction and leveled off until 2005. Moreover, there is evidence for the capability of FDI to close the technology gap as well as for sectoral differences in technology diffusion. Young and Lan (1997) present survey results from the city of Dalian in Northeast China indicating that the source of FDI and the sector matter for technology diffusion. On average, 39% of FDI are reported to involve a technology gap of at least 10 years compared with the technology in practise in China. 68% of this share are in turn reported to be to some extent or completely internationally transferable.

[13] The results by Branstetter and Lardy (2006) support the choice of labor productivities as a productivity and technology measure.

[14] Coe and Helpman (1995); Coe et al. (1997); Van Pottelsberghe de la Porterie and Lichtenberg (2001); Aitken and Harrison (1999); Hejazi and Safarian (1999); Xu and Wang (2000); Keller and Yeaple (2009); Ciruelos and Wang (2005); Lee (2005); Zhu and Jeon (2007) are a few examples.

[15] Wei (1993); Berthélemy and Démurger (2000); Sun and Parikh (2001); Lai et al. (2006); Liu (2008); Kuo and Yang (2008).

[16] There is a plausible reason why vertical spillovers are stronger than horizontal spillovers: Firms need to share knowledge with customers and suppliers within the production chain in order to work together successfully. On the contrary, firms try to avoid spillovers to rivals within the same sector.

be stronger than through imports (regarding China c.f. Lai et al., 2006). We use the empirical evidence as a starting point for choosing the parameter values. Herein, we assume technology diffusion via FDI through backward linkages to be stronger than through forward linkages, forward linkages to be stronger than horizontal linkages, and the latter to be slightly stronger than technology diffusion through imports. Herein, we include less sectors in technology diffusion via imports than via FDI.

(2) We compare growth rates of China's labor productivity and GDP in the benchmark year produced by the model with observed growth rates (World Bank, 2008b).[17] Furthermore, we compare future GDP and GDP growth rates with forecasts by OECD (2008). Moreover, we choose exogenous growth rates of total factor productivity in *IND* (0.86% p.a.) and *DEV* (1.3% p. a.) such that the GDP in 2030 produced by the model matches the OECD forecasts.

(3) Herein, several estimates give an idea of the share of productivity growth that can be attributed to FDI (and imports).[18]

(4) Finally, IEA (2007) focusing on China and India provides forecasts of future emissions distinguished by fossil fuel sources. In scenario *blue*, we adjust the regional supply elasticities of coal, gas and oil such that the resulting regional emissions stemming from coal, gas and oil come to those in the *Reference Policy Scenario* for 2030.[19] In scenario *brown*, we raise the exogenous part of general technological progress in China to 2%p.a. and switch off any international technology diffusion. This creates lower economic growth in early periods, but higher economic growth in later periods. The model's emissions of China in 2030 come close to those in the *High Growth Scenario* by IEA (2007).

Table A1 in the Appendix gives an overview of sectoral indicators in the benchmark situation.[20] Note that a high foreign capital intensity and a high relative labor or energy productivity gap result in high labor or energy productivity growth in this sector. Moreover, Table A2 contains relevant parameter values. Table A3 compares model outcomes under the different technology scenarios to reference data described above.

6. Energy efficiency gains via FDI and imports

For the purpose of climate and energy modeling, we are especially interested in energy specific technology diffusion. In general, one expects that energy technologies diffuse jointly together with other technologies, since energy saving characteristics are connected to other technological advances in the same product such as a machine or a vehicle. However, technological progress is directed towards certain production factors depending on (relative) factor prices and factor supplies (Acemoglu, 2002). In our model, this aspect is set exogenously in the calibration.

Referring to the empirical literature, several studies show that foreign ownership of firms is correlated with better energy efficiency.[21] And it is known that standard Chinese coal fired electricity power plants, which account for 75% of electricity generation, are about 5 to 10% less efficient than power plants in industrialized countries (c.f. Blackman and Wu, 1998).[22] Only few studies specifically examine the influence of trade and FDI on energy and emissions in the destination country (Cole, 2006; Perkins and Neumayer, 2009; Hübler and Keller, 2010, for overviews see IPCC, 2000; Murphy et al., 2005 and Peterson, 2008).[23] Estimations by Fisher-Vanden et al. (2006) show that technologies imported to China are labor and energy saving and capital and materials using, whereas internal technology development in Chinese firms is capital and energy saving and labor and materials using. Zhang (2003) shows that the decline in real energy intensitiy explains the decline in energy use in China's industry sector in the 1990s, which supports modeling energy efficiency improvements explicitly. Lin and Polenske (1995) and Garbaccio et al. (1999) show that changes in subsectoral intensities explain the main part of the decline in China's energy intensity in the 1980s, which supports the implementation of a sectoral diffusion model.

6.1. Methodology

This subsection transfers the mechanism derived in the previous section to energy specific technology diffusion. The following Eq. (6) differs from Eq. (3) in three respects. First, in Eq. (3) technology diffusion enhances total factor productivity, i.e. the output quantity (domestic sales plus exports in Fig. 1) given certain input quantities. Now, technology diffusion ceteris paribus reduces the necessary energy input quantity (the energy input in Fig. 1) to produce a certain output quantity; thus Eq. (6) has a negative sign. Second, labor productivities as efficiency measures are replaced by energy productivities. Herein, the simulations yield energy inputs in value form, which depend on energy prices that differ significantly across regions. In order to derive an inter-regionally comparable measure, we compute real energy input E_R^{it} in a region $R=\{CHI, IND, DEV\}$ in a certain sector i at time t in the following way:

$$E_R^{it} = \frac{e_R^{it}}{e_R^{i,2004}} \rho_R^{2004} \tag{5}$$

$e_R^{it}/e_R^{i,2004}$ denotes the ratio of the energy input value in year t relative to the energy input value in the base year 2004. ρ_R^{2004} is the physical energy input (in Giga Joule) in 2004 given by the GTAP 7 data.[24]

The μ parameters in Eq. (3) are renamed by corresponding η parameters. Now b_{CHI} represents autonomous energy efficiency improvements.

$$\begin{aligned}\frac{\Delta E_{CHI}^{it}}{E_{CHI}^{it}} = & -\phi_{CHI}^{t}\eta_{CHI} \\ & \cdot\left(\eta_K \frac{K_{IND}^{it}}{K_{CHI}^{it}} + \eta_M \frac{M_{IND}^{it}}{Y_{CHI}^{it}} + \eta_B \sum_{b;b\neq i} \frac{K_{IND}^{bt}}{K_{CHI}^{bt}} \frac{D_{CHI}^{ibt}}{Y_{CHI}^{it}} + \eta_F \sum_{f;f\neq i} \frac{K_{IND}^{ft}}{K_{CHI}^{ft}} \frac{D_{CHI}^{fit}}{Y_{CHI}^{it}}\right) \\ & \cdot\left(\frac{\frac{Y_{IND}^{it}}{E_{IND}^{it}}}{\frac{Y_{CHI}^{it}}{E_{CHI}^{it}}} - 1\right) + b_{CHI}\end{aligned} \tag{6}$$

This mechanism leads ceteris paribus to a reduced energy input necessary to produce a certain output in the production structure in Fig. 1. Herein, we model only exogenous energy efficiency improvements without international technology diffusion in region *IND* and no energy specific technological progress in region *DEV*.

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[17] For estimated sectoral productivity growth rates in China see Mai et al. (2004).

[18] Sun and Parikh (2001); Tseng and Zebregs (2002) and Whalley and Xin (2006) for China, Rattsø and Stokke (2003) for Thailand.

[19] CO_2 emissions in Gt derived from the IEA (2007) *Reference Scenario* are 11.5 in *CHI*, 15.3 in *DEV*, 15.1 in *IND* and 41.9 in total. Our simulations yield higher emissions stemming from oil in *IND* and *DEV* so that emissions are 11.2 in *CHI*, 17.3 in *DEV*, 17.1 in *IND* and 45.6 in total.

[20] Table A1 reveals a very high labor productivity and a very low energy productivity of gas supply. The relative energy productivity gap is also large resulting in strong improvements in energy productivity. This phenomenon is an outlier in the GTPA 7 data.

[21] Eskeland and Harrison (2002) for Mexico and Cote d'Ivoire. Fisher-Vanden et al. (2004) for China.

[22] For an analysis of carbon emissions in the Chinese power sector see Zhang et al. (2006).

[23] A broader literature strand deals with the impact of globalization on the environment using SO_2 emissions as an indicator for environmental quality (especially Antweiler et al., 2001, Copeland and Taylor, 2005).

[24] This method corrects for regional differences in energy prices in the base year, but it does not take regional differences in future energy price increases into account.

6.2. Calibration

This subsection explains the parameterization of Eq. (6) based on the parameter values used for Eq. (3). As before, we assume that FDI inflows cause efficiency gains in most sectors while imports only lead to efficiency gains in production of machinery and agriculture (see Table A2 in the Appendix). Besides the information used in section 5, we use the following information to calibrate the model:

(1) Van der Werf (2007) provides estimations of rates of energy specific technological change. The rates vary between 1.27% and 2.75%p.a. in high-income European countries. Blanford et al. (2008) suggest a rate of autonomous energy efficiency improvements of 1% for industrialized countries. They point out that it is not clear whether energy intensities rise or fall in developing countries. Accordingly, we set the rates of autonomous energy efficiency improvements in all three regions to 1%p.a. When calibrating energy specific technology diffusion into China, we compare the growth rate of energy productivity produced by the model with observed growth rates (World Bank, 2008b, also China Statistical Yearbook, 2006, 2007).[25]

(2) The inclusion of energy saving technology diffusion leads to scenario *green* with relatively low emissions. As a reference point, we compare China's emissions in 2030 with *Alternative Policy Scenario* by IEA (2007) with low emissions.

The parameter values and the comparison of model results with reference data are reported in Tables A2 and A3 in the Appendix.

7. Policy analysis

This section applies the mechanisms derived in the previous sections to a post-Kyoto climate policy analysis. We assume a per-capita emissions based contraction and convergence (C&C) regime which reduces regional emissions gradually so that equal regional per capita emissions will be reached in the future (c.f. GCI, 1990, Meyer, 2004).[26] C&C has been frequently discussed by prominent politicians and economists as a mechanism that yields a “fair” distribution of emissions permits: Population rich developing countries such as China or India receive relatively large endowments of emissions permits. Allowing for inter-regional emissions trading, such developing countries can then receive revenues from selling emissions permits to industrialized countries. This is often seen as one channel of financial transfer from industrialized to developing countries; that is an indirect way to support emissions reductions in developing countries.

We assume 2020 as a start year for the introduction of a climate policy regime including China and other developing countries (c.f. Stern, 2008 and Zhang, 2009a,b).[27] The emissions constraints for each region start at their business as usual (BAU) levels of per capita emissions in 2019 and then gradually decline from 2020 on so that per capita emissions of each region amount to 2t of CO_2 in 2050 (c.f. Stern, 2008). The mathematical formulation of the contraction and convergence mechanism strictly follows Böhringer and Welsch (2004). The resulting global emissions in 2050 amount to about 18.6Gt of CO_2. The scenario aims at reaching the 2° target as emphasized in Copenhagen 2009.

Table 1
Regional impacts of introducing a C&C policy on welfare and emissions under different technology scenarios.

Scenario		*blue*		*green*		*brown*	
Global ETS		No	Yes	No	Yes	No	Yes
Accum. welfare change in %	*CHI*	−1.1	−0.2	0.0	0.7	−4.1	−3.9
	DEV	−3.9	−3.5	−2.9	−2.6	−4.2	−3.6
	IND	−1.2	−0.8	−0.9	−0.6	−1.2	−0.9
Accum. CO_2 change in %	*CHI*	−41.9	−49.5	−34.5	−47.0	−53.0	−51.6
	DEV	−27.2	−34.7	−28.3	−34.3	−24.6	−35.8
	IND	−35.0	−33.7	−35.0	−22.8	−33.6	−23.4

Like Böhringer and Welsch (2004), we run each technology scenario (blue, green and brown) without climate policy (BAU), with C&C and a global emissions trading scheme (ETS) and with C&C, but without an emissions trading scheme (no ETS). Herein, ETS allows inter-regional trade of emissions permits at each point of time, but no inter-temporal trade of permits.

We can basically distinguish three factors that raise regions' demand for emissions permits: First, higher marginal abatement costs given by less advanced technologies and more restricted substitution possibilities between production inputs and outputs. Second, higher economic growth. Third, a smaller population size with respect to a per capita based allocation framework. China has a comparative advantage regarding the first and the third factor, while it has a comparative disadvantage regarding the second factor. Also, there is high uncertainty regarding the second factor, i.e. China's future economic growth rates.

The results of the simulations show that the foreign capital intensity (value of foreign capital relative to the value of domestic capital) steadily declines over time in each Chinese sector, on average across all 30 sectors from less than 14% in 2004 to 6% in 2030 in scenario *blue* (BAU). Meanwhile, the absolute value of foreign capital steadily increases in each Chinese sector over time due to economic growth.

Fig. 2A in the Appendix illustrates the Chinese growth rates of labor productivity and energy productivity over time that follow from the model calibration for the three BAU scenarios.

Fig. 3A in the Appendix illustrates the resulting regional emissions paths for the three technology scenarios. In per capita terms, emissions amount to 2t of CO_2 in all regions in 2050 under C&C without ETS. With ETS we find the following per capita emissions in 2050: In scenario *blue* 2t of CO_2 in *CHI*, 1 in *DEV* and 7 in *IND*; in scenario *green* 1 in *CHI*, 2 in *DEV* and 6 in *IND;* and in scenario *brown* 2 in *CHI*, 1 in *DEV* and 6 in *IND*. Thus, clearly, the industrialized countries buy emissions permits from the developing countries, because marginal abatement costs are lower in developing than in industrialized countries.

Within each scenario, we compute the welfare effect of the C&C policy with and without ETS relative to BAU.[28] The welfare effect is computed as follows: First, we compute the Hicks-equivalent variation of expenditures between BAU and the policy scenario for each region. Second, we sum up the Hicks-equivalent variations of each year discounting at a rate of 2%p.a., which yields the overall welfare effect for each region over the time frame 2004 to 2050. Note that we do not take the avoidance of climate damages into account that is expected to create a positive welfare effect of climate policy in total. We do not take capital stocks into account that remain at the end of the time horizon, either. The resulting welfare effects are reported in Table 1. Table 1 also reports relative changes in regional emissions cumulated from 2004 until 2050.

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[25] World Bank (2008b) data show that the yearly improvement of energy productivity in China was slightly higher than the yearly improvement of labor productivity between 1980 and 2001, namely above 6% p.a. resulting in a decline in energy intensity. On the contrary, the Chinese energy productivity dropped by 3.4% in 2003 and by 5.4% in 2004. It improved again by 1.8% in 2005.

[26] For a CGE analysis of contraction and convergence see Böhringer and Welsch (2004), for a growth model analysis see Leimbach et al. (forthcoming), also see Leimbach (2003).

[27] We do not start with an intensity target for China, though, considering that in case of deterministic economic growth we can replace intensity targets by absolute targets.

[28] The reference BAU thus changes between scenarios *blue, brown* and *green*.

The magnitudes of the welfare effects are in accordance with Böhringer and Welsch (2004) and with Leimbach et al. (2010).[29] As suggested by theory, welfare losses due to the introduction of emissions caps are lower in the presence of an ETS that leads to an equalization of marginal abatement costs. In the presence of the ETS, China and the other developing countries reduce emissions to a larger extent and the industrialized countries to a smaller extent than in the absence of the ETS. This shows again that *CHI* and *DEV* sell emissions permits, while *IND* buys emissions permits, because marginal abatement costs are possibly lower in *CHI* and *DEV* than in *IND* and *CHI* and *DEV* have large population sizes.

Focussing on China, we notice that only in scenario *green* (ETS) China gains a small positive welfare effect of about 0.7% when introducing C&C. This happens because China can substantially reduce emissions through energy specific technology diffusion. Since economic growth and emissions growth are moderate and decrease over time, China can sell superfluous emissions permits to the industrialized region and gather substantial revenues. This positive welfare decreases to about 0.3% when reducing the elasticity of substitution between capital, labor and energy in main production (ε_{KLE}) from 1 to 0.5. It changes to about 0.5% when halving the strength of energy specific technology diffusion (η_{CHI}) (keeping $\varepsilon_{KLE}=1$). When not allowing for international emissions permit trade, there is almost no welfare change (only slightly below zero). This means, the C&C emissions caps do not hinder Chinese growth in the presence of energy saving technology diffusion. In scenario *blue*, on the contrary, the model yields a welfare loss for China of 1.1% without ETS and 0.2% with ETS.[30] Hence, even without energy specific technology diffusion, emission permit trade can almost compensate the welfare loss due to C&C. However, assuming sustained high Chinese growth without energy specific technological progress in scenario *brown*, the welfare loss for China due to C&C rises to about 4%, no matter with or without ETS. This result appears intuitive, since high economic growth creates substantial emissions in the distant future, while at the same time emissions cuts become substantial in the distant future. Fig. 3A in the Appendix also clearly shows that sustained high growth of China in scenario *brown* creates a surge for resources and products that negatively effects growth of the developing region. Also, in scenario *brown* China does not sell permits for a long period of time since it requires its permits to cover its own emissions.

According to the results, the other developing countries suffer relatively high welfare losses of up to more than 4%. This result is surprising when considering the large populations of many developing countries which entitle them to receiving large amounts of emissions permits under C&C.[31] On the contrary, economic growth and emissions growth are persistently high in *DEV* (like in China in scenario *brown*) so that the C&C emissions caps require severe emissions cuts compared to BAU. Additionally, *DEV* includes fossil fuel extracting and exporting countries that suffer from cutting energy demand through climate policy. However, assuming exogenous energy saving technological progress in scenario *green* significantly reduces the welfare loss. Assuming energy saving technology diffusion into *DEV* like into *CHI* could further reduce the welfare loss.

Finally, according to the results, the industrialized countries suffer relatively low welfare losses of around 1% because their economic growth and emissions growth are relatively low.

8. Conclusion

This paper introduces a mechanism of endogenous sectoral international technology diffusion via FDI and imports into recursive-dynamic CGE modeling for climate policy analysis. As a novel feature, the mechanism distinguishes horizontal spillovers (within sectors) and vertical spillovers (across sectors in the production chain) following the econometric literature on technology spillovers. The mechanism is not only applied to technology diffusion in general but also to energy specific technology diffusion. The mechanism is calibrated using diverse sources of empirical evidence focusing on China. Since technology diffusion is not only connected to trade, but also to FDI, a mechanism of international capital mobility is implemented and calibrated to Chinese data.

The paper then applies the model to the analysis of a contraction and convergence type climate policy focusing on mainland China. Climate policy starts in 2020 and leads to equal per capita emissions of 2t of CO_2 in 2050. According to the results, in the presence of energy saving technology diffusion and inter-regional emissions permit trading, mainland China could benefit from climate policy (not considering climate change damages), as long as general economic growth rates decline over time in a convergence process. Even in the absence of energy saving technology diffusion, permit trade could compensate China's cumulated discounted welfare loss due to emissions cuts. On the contrary, if China is able to sustain high growth without achieving substantial improvements in energy intensity welfare losses can reach up to 4%.

These results emphasize the importance of fostering international technology diffusion, especially energy saving technology diffusion. But international diffusion of energy saving technologies might not occur automatically. It probably requires active support by China's economic policy, China's trading partners' economic policies as well as international climate policy. Herein, a per capita based distribution of emissions permits creates indirect financial assistance for China. Under these preconditions, joining a global climate policy regime appears better acceptable for China.

However, like in other climate policy models, there are uncertainties in the choice of functional forms (such as the mechanism of technology diffusion) and of parameter values such as the substitutability of energy with other production factors and the technology spillover strength. This is especially true with respect to energy specific technology diffusion. There are also uncertainties in population growth and exogenous technological progress, which are main drivers of emissions. Given the nest structure of the model and the related elasticities of susbtitution, China's marginal abatement costs appear to be rather low. And without doubt, a CGE model assuming perfect markets cannot capture the numerous market imperfections in China or elsewhere.

Future research can combine the methodology of international technology diffusion with an approach of endogenous technological change (e.g. like Bosetti et al., 2008). Herein, one may build on the theoretical work on endogenous growth (e.g. Aghion and Howitt, 2009) and directed technical progress (e.g. Acemoglu, 2002). Since technology diffusion is modeled on the sectoral level accounting for sectoral linkages, the novel mechanism appears suitable for the analysis of sectoral climate policy measures.

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[29] The results are not directly comparable, since the BAU and policy emissions levels are not identical, nevertheless, they are similar. Also, contraction and convergence starts in 2000 in Böhringer and Welsch (2004) and in 2010 in Leimbach et al. (2010). Equal per capita emissions are reached in 2050 in both studies.

[30] Böhringer and Welsch (2004) estimate a welfare loss for China of about 3% without ETS and of about 1% with ETS.

[31] Böhringer and Welsch (2004) find welfare effects in developing countries reaching from over 17% for Africa and India to almost −9% in the region consisting of the former Soviet Union and Central and Eastern Europe. Disentangling the welfare effects in our analysis would require a disaggregation of the developing region. The focus of this paper is, however, on China.

Appendix A

Table A1
Indicators of the Chinese economy in the benchmark year 2004. The values are computed according to the terms in Eq. (3) and Eq. (6). (For an explanation of the sector abbreviations see footnote 3 in Section 2)

	Technology diffusion		Foreign capital	Imports	Intermediate goods supply	Labor productivity	Energy productivity	Labor productivity	Energy productivity
	FDI	Imports	% of all capital	% of output	% of output	1000 US-$ per worker	US-$ per Joule	Relative gap	Relative gap
CHI Ø			9.4	12.7	69.3	4.1	3.0	13.1	2.1
AGR	x	x	1.3	6.1	56.7	2.1	4.5	40.3	1.3
BEV	x		12.0	1.5	43.3	7.2	8.0	19.2	2.2
BUI	x		15.3	7.2	79.8	3.0	11.0	15.6	2.1
COL	x		1.7	1.6	89.0	2.6	1.7	35.2	2.2
COM	x		3.7	1.5	75.5	4.0	6.3	13.8	4.4
CON	x		1.7	0.4	99.7	4.2	19.4	9.2	2.8
CRP	x		26.0	31.2	79.2	6.4	1.2	15.0	1.2
CRU	x		1.3	78.3	97.9	6.7	1.2	31.1	5.6
CUS			9.9	4.3	39.4	2.1	7.4	24.8	1.2
ELE	x		5.3	0.2	85.8	7.2	0.3	14.2	2.4
ELM	x	x	59.6	41.0	37.2	8.5	21.5	13.7	0.2
FEM	x		10.9	10.9	93.2	5.2	1.0	20.1	1.6
FIN	x		0.6	5.3	79.7	3.0	13.5	12.2	2.6
GAS	x		16.6	0.0	74.7	51.2	0.1	1.6	22.6
MAC	x	x	14.0	37.0	68.7	4.8	8.7	12.3	2.4
MET	x		18.2	6.9	71.5	5.4	4.6	10.1	2.9
MIN	x		1.4	37.1	93.5	2.7	2.0	33.2	0.6
NFM	x		20.3	28.3	86.6	7.3	1.1	14.3	1.8
NMM	x		20.0	3.8	81.0	3.5	0.9	19.9	2.5
OIL			22.4	10.3	39.4	27.9	–	48.8	–
OTM	x	x	6.8	3.4	44.3	4.5	36.2	17.9	−0.3
PAP	x		27.4	14.7	91.9	4.4	2.7	14.0	1.3
PUB			2.3	1.5	39.4	1.3	5.7	19.0	2.3
REE			20.3	–	39.4	–	–	–	–
TEX	x		17.7	10.8	44.1	5.1	6.2	17.5	1.6
TRD	x		5.5	8.5	68.6	2.9	5.6	13.2	1.9
TRM	x	x	51.3	17.2	78.4	5.6	7.6	17.0	4.8
TRN	x		3.9	4.5	73.8	2.7	1.0	21.5	0.4
WAT	x		6.0	0.9	67.3	2.3	1.0	25.0	3.8
WOO	x		4.3	5.9	65.1	4.7	10.5	12.4	0.5

Table A2
Parameter values for the CGE analysis (examined alternative values in parentheses).

Symbol	Name	Value	Symbol	Name	Value
ξ_G	Elast. of subs. of Armington goods from different regions	8	$\mu_K = \eta_K$	General/energy saving spillover strength of foreign capital	1
ξ_{MD}	Elast. of subs. of imports vs. domestic goods	4	$\mu_M = \eta_M$	General/energy saving spillover strength of imports	1.5
τ	Elast. of trans. of exports vs. domestic goods	2	$\mu_B = \eta_B$	General/energy saving spillover strength of backward linkages	3
ε_{KIND}	Elast. of transf. of domestic and foreign capital assets in *IND*	2	$\mu_F = \eta_F$	General/energy saving spillover strength of forward linkages	1.5
ε_{KCHI}	Elast. of subs. of foreign and domestic capital in *CHI*	1	a_{IND}	Rate of exogenous general technical progress in *IND* p.a.	0.86%
ε_{KLE}	Elast. of subs. of capital, labor, energy	1 (0.5)	a_{CHI}	Rate of exogenous general technical progress in *CHI* p.a.	0.5 (2)%
ε_R	Elast. of subs. of land with capital–labor–energy composite	0.1	a_{DEV}	Rate of exogenous general technical progress in *DEV* p a.	1.3%
φ_{CHI}	Benchmark human capital level of *CHI*	1.019	b	Rate of exogenous energy saving technical progress in regions p.a.	1%
μ_{CHI}	General spillover strength in *CH*	0.0025	ρ	Welfare discount rate p.a.	2%
η_{CHI}	Energy specific spillover strength in *CHI*	0.05			

Table A3
Indicators of the Chinese economy, comparison of model outcomes with reference data.

Indicator	Source	Refer. value	*blue*	*green*	*brown*
GDP growth 2005 (1980–2006) (%)	World Bank (2008b)	10.4 (9.9)	10.7	11.5	8.7
Labor prod. growth 2005 (1980–2006) (%)	World Bank (2008b)	9.5 (7.2)	8.0	8.5	7.7
– Via FDI technology spillover	Tseng and Zebregs (2002); Whalley and Xin (2006)	1.6–2.5	3.0	3.2	–
– Herein vertical/horizontal		–	1.9/1.1	2.1/1.1	–
– Via import technology spillover	–	–	0.9	0.9	–
Energy prod. growth 2005 (1980–2006) (%)	World Bank (2008b)	1.8 (5.4)	0.2	3.3	0.3
GDP growth 2020–2030 (%)	OECD (2008)	4.0	2.7	2.7	5.1
GDP 2030 (trill. US-$)	OECD (2008)	6.372	6.271	6.594	8.726
Emissions 2030 (Gt CO2)					
– Reference Policy Scenario	IEA (2007)	11.5	11.2	–	–
– Herein coal/oil/gas		9.0/2.1/0.4	9.0/2.1/0.1	–	–
- Alternative Policy Scenario		8.9	–	8.5	–
– High Growth Scenario		14.1	–	–	14.1

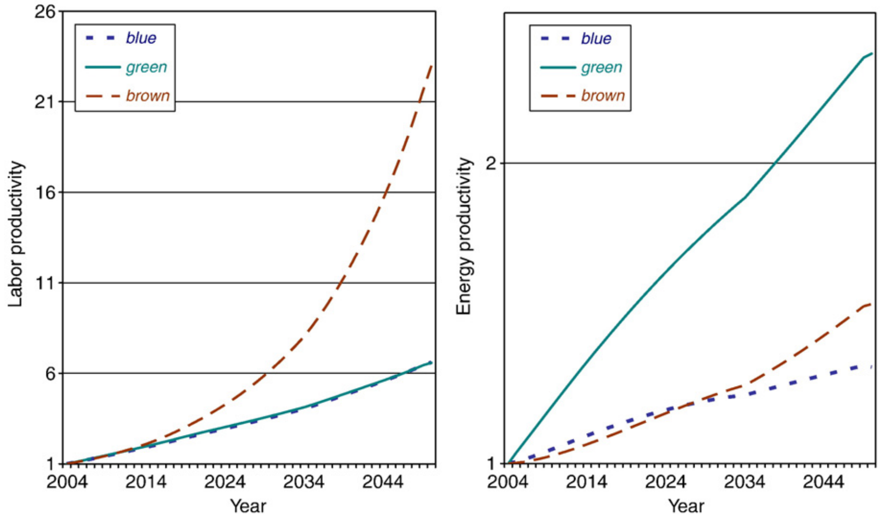

Fig. 2A. Time paths of China's BAU labor and energy productivity (relative to the values in the benchmark year 2004).

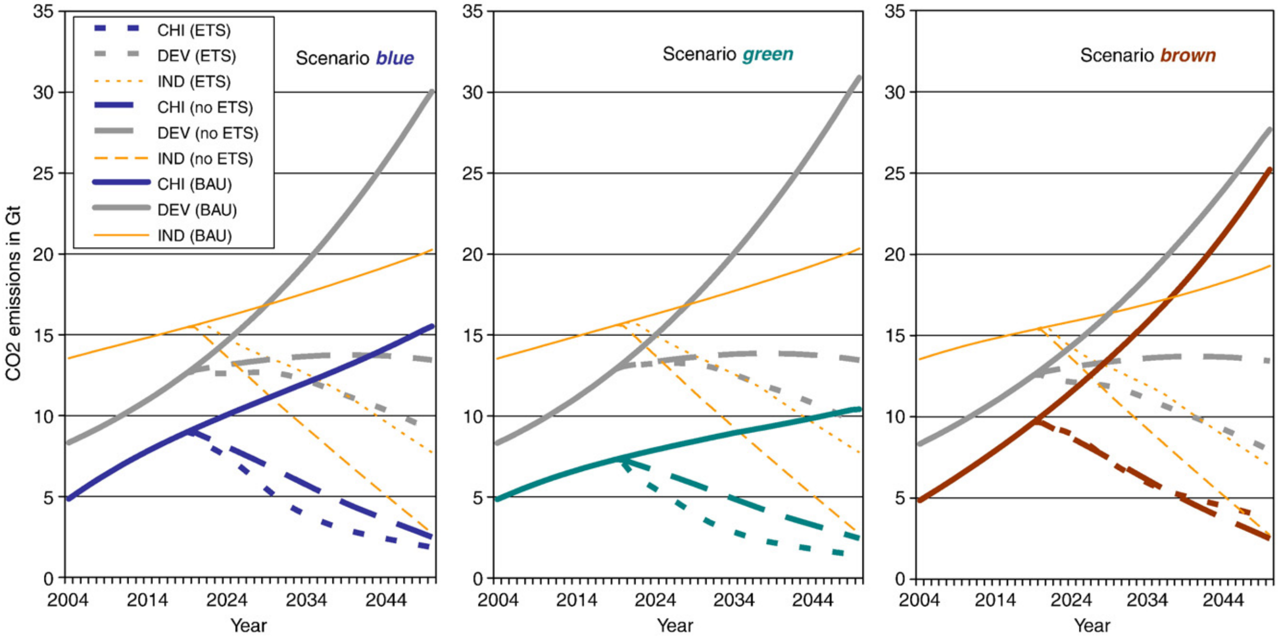

Fig. 3A. Time paths of regional emissions.

Appendix B. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.eneco.2010.09.002.

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