Can Carbon Based Tariffs Effectively Reduce Emissions? A Numerical Analysis with Focus on China

Michael Hübler

March 8, 2011

Abstract

(1) We estimate CO_2 implicitly exported via commodities relative to a region's total emissions: We find -15% for the industrialized, 10% for the developing region, and 25% for China. (2) We analyze a Contraction and Convergence climate regime in a CGE model including international capital mobility and technology diffusion: When China does not participate in the regime and instead a carbon tariff is imposed on its exports, it will likely be worse off than when participating. This result does not hold for the developing region in general. Meanwhile, the effect on emissions appears small.

JEL Classifications: F13, F18, Q54

Keywords: carbon content of trade, border tax adjustment, climate policy, contraction and convergence, developing countries, China

1 Introduction

The necessary drastic reduction in global CO_2 emissions critically depends on the inclusion of the developing and emerging economies, especially of China. – If China stays reluctant to join a binding post-Kyoto regime, China's emissions can possibly be reduced by imposing a carbon tariff, or carbon content based border tax adjustment, since the Chinese economy is carbon as well as export intensive.[1] Such a carbon tariff could also be used as a threat in order to convince China to join a post-Kyoto climate regime. Such policies are currently controversially debated (Krugman 2009, Friedman 2009, Broder 2009: "Obama Opposes Trade Sanctions in Climate Bill"). Also, the accordance with WTO law is a critical aspect. For example, Bhagwati and Mavroidis (2007) question the economic, juristic and political feasibility of carbon content based border tax adjustment (BTA). The main research task of our article is therefore to assess how a carbon tariff on exports from China in comparison with a carbon tariff on exports from the other developing countries affects welfare and emissions of China, the developing and the industrialized countries.

Several studies have recently estimated carbon emissions implicitly embodied in traded commodities for different countries and specifically for China.[2] Shui and Harriss (2006) estimate that US CO_2 emissions would be 3 to 6% higher if the goods imported from China were produced in the USA, and that 7 to 14% of China's CO_2 emissions can be attributed to exports for US consumers.

Peters and Hertwich (2008) calculate carbon contents of trade based on the GTAP 6 data set for 2001. They find net carbon imports for the Annex B region of 5.6% relative to total CO_2 emissions produced in this region, and relative net carbon exports of 8.1% for the non-Annex B region.[3] In particular, according to their calculations China's net carbon exports amount to 17.8% of its total produced emissions, US net carbon imports amount to 7.3%, Japan's to 15.3%, and Germany's to 15.7%. Switzerland (122.9%) and Latvia (60.7%) are the most intensive net carbon importers among Annex B countries, while Hong Kong (182.2%), the rest of South African CU (176.4%) and Mozambique (172.4%) are the main net carbon importers among all countries. South Africa (38.2%)

---

[1] The term 'border tax adjustment' (BTA) is frequently used in the debate and usually refers to taxes on imports in combination with tax rebates on exports from a region with a higher tax than in the trade partner region.

[2] For a "review of input-output models for the assessment of environmental impacts embodied in trade" see Wiedmann et al. (2007). For an overview of quantitative analyses of CO_2 embodiment in international trade see Liu and Wang (2009).

[3] Herein, net carbon exports mean implicit CO_2 exports via exports of commodities minus implicit CO_2 imports via imports of commodities.

and the Russian Federation (21.6%) are the most intensive net carbon exporters among all countries.

Pan et al. (2008) estimate China's emissions in 2006 on a consumption basis using data from Input-Output Tables of China in 2002 (NBS 2006), the China Statistical Yearbook (various years), the International Energy Agency (IEA 2006, 2007) and the World Resources Institute (WRI). They apply the "Leontief inverse" matrix and distinguish imported from domestically produced intermediate goods, which is often neglected in the literature. As a result, they find emissions amounting to 3.8Gt of CO_2 rather than 5.5Gt on the standard production basis. This implies that China's net carbon exports amount to 1.7Gt in 2006. They conclude: "Moreover, in the current institutional context, production methodologies encourage leakages through trade that may do more to displace than to reduce emissions. Both equity and efficiency concerns therefore suggest that emissions embodied in trade should receive special attention in the distribution of post-Kyoto abatement burdens." Accordingly, our CGE (computable general equilibrium) analysis captures supply and demand side carbon leakage between regions with and without climate policy.

In the CGE model based literature, Babiker and Rutherford (2005) and Bhringer et al. (2010) find that border tax adjustment has a limited potential to reduce carbon leakage. Moreover, possible competitiveness disadvantages for firms within the European emissions trading scheme towards non-EU firms play a central role. Alexeeva-Talebi et al. (2008a) compare border tax adjustment based on imported *quantities* multiplied by domestic carbon intensity factors with an integrated emissions trading scheme based on imported *emissions* actually created during the production of imported commodities. They conclude that border tax adjustment protects domestic competitiveness more effectively, while an integrated emissions trading scheme achieves a greater reduction in emissions abroad. Alexeeva-Talebi et al. (2008b) conclude from their simulations of the European emissions trading scheme that market based policy measures such as the Clean Development Mechanism, allowing for flexibility in the location of emissions savings, can be effective substitutes for border tax adjustments in unilateral climate policy. Manders and Veenendaal (2008) find that border tax measures under the European emissions trading scheme significantly reduce carbon leakage. Furthermore, border tax measures appear beneficial for the EU, while they may entail a welfare loss for the rest of the world. Herein, most of these studies use the GTAP 6 data for the base year 2001, while our study uses the GTAP 7 data for 2004. Moreover, we focus on China as a carbon as well as export intensive exporter, in comparison with the other developing countries.

Finally, Lessmann et al. (2009) examine a numerical, intertemporal optimization framework with stable coalitions. They show that carbon based import tariffs increase the emissions target coalition in a welfare improving way if the tariff rate is small relative to the Armington elasticity of imports.

The first contribution of our paper is to calculate and illustrate implicit carbon contents of commodities traded between (mainland) China, the industrialized countries and the developing countries using the GTAP 7 data for 2004 and distinguishing intermediate inputs by source country (section 3). The second contribution is to examine the welfare and emissions effects of imposing a carbon tariff on exports from China and the other developing countries under a Contraction and Convergence climate regime with emissions trading (section 4). Herein, we apply a computable general equilibrium (CGE) model that includes international capital mobility (foreign direct investment, FDI) and an innovative way of modeling international technology diffusion via capital mobility and trade, distinguishing vertical and horizontal spillovers. This feature appears important when analyzing trade policy in combination with climate policy, because trade and FDI may create emissions reductions via technology spillovers. Based on the results, the paper derives implications for post-Kyoto policies (section 5). The paper starts with an overview of the underlying three region model (section 2).

2 The three region model

The underlying DART[4] model is a recursive dynamic multi-region, multi-sector CGE model of the world economy. The static part of the model is currently calibrated to the GTAP 7 database (Narayanan and Walmsley 2008) that covers global production and trade data (including taxes and subsidies, governments and households, consumption and savings) for 113 countries and regions, 57 sectors (commodities) and 5 production factors (skilled and “unskilled” labor, capital, land, natural resources) for the benchmark year 2004.[5] Carbon emissions are derived from the use of fossil fuels in production and for consumption in combination with the associated carbon intensity factors of coal, gas and oil. The model runs under GAMS MPS/GE. For a detailed description see Klepper and Springer (2000), Springer (2002) and Klepper et al. (2003) and Hübler (2011).

The GTAP data can be aggregated according to modelers’ needs. The version of the model scrutinized here distinguishes three regions: (mainland) China (CHI), industrial-

---

[4] Dynamic Applied Regional Trade.

[5] The GTAP data are collected from various data sources and merged together to a consistent data set. For detailed information see *https : //www.gtap.agecon.purdue.edu/*.

ized region (IND) and developing region (DEV). The industrialized region encompasses the OECD countries plus Hong Kong, Macao, Taiwan, Singapore and South Korea, since they are important sources of FDI into (mainland) China – and potential sources of technology transfer into (mainland) China (compare Tseng and Zebregs 2002, Whalley and Xin 2006). The model distinguishes the production factors labor, capital, land, and natural resources (fossil fuels). In order to analyze climate policies, CO_2 emissions are linked to the use of fossil fuels in production and consumption. The current sectoral aggregation covers 30 sectors in each region.

Each commodity market is perfectly competitive. Product and factor prices are fully flexible. The model incorporates two types of agents for each region: producers (one producer per production sector and region) and consumers (one private and one public consumer per region). Producer behavior is derived from cost minimization for a given output. Consumers receive all income generated by providing primary factors to production processes. Consumers save a fixed share of income and invest it into capital for production in each period. Herein, investments are produced like commodities by using production inputs. The disposable income (net of savings and taxes) is then used for utility maximization by purchasing and consuming commodities. The expenditure function is modeled as a CES (constant elasticity of substitution) composite, which combines an energy bundle with a non-energy bundle.

Factor markets are perfectly competitive with full employment of all factors. Labor is a homogenous good, being mobile across industries within regions, but being internationally immobile. While in the basic version of the DART model capital is also internationally immobile, in this version capital is internationally mobile between the industrialized region and China. The benchmark values of foreign capital located in China are taken from the China Statistical Yearbook (2006, 2007). All regions are linked by bilateral trade flows, and all commodities except the investment good are traded among regions. Domestic and foreign commodities imported from different regions are imperfect (Armington) substitutes.

The 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 investment in capital. The model assumes constant, but regionally different growth rates of human capital (educational attainment) taken from Hall and Jones (1999). Population growth rates and labor participation rates are taken from the PHOENIX model (Hilderink 2000). The resulting GDP growth paths are in line with recent projections by OECD (2008).

Technological progress has an exogenous part in every region. It consists of improvements in total factor productivity and in energy biased technological progress. In the latter case, a given output quantity can ceteris paribus be produced with a smaller volume of energy inputs. In (mainland) China, technological progress in a certain sector additionally increases with the import intensity of the related product, with the foreign capital intensity in this sector (horizontal linkage) and with forward and backward linkages (vertical linkage) across sectors within the production chain. Technological progress decreases the closer the Chinese technology level comes to the technology frontier given by the industrialized region. This results in a process of technological convergence.[6] This novel way of modeling international technology diffusion via FDI and trade appears important when analyzing trade policy in combination with climate policy.

Like other CGE models, DART has a number of limitations: In China, as well as in any other country, markets are far from perfect with respect to perfect competition, market clearance, immediate adjustment without adjustment costs, and so forth. As a consequence, reactions to shocks such as new policies, occur fast and do not incorporate all relevant associated costs. Moreover, the model is bound to the benchmark situation in certain respects, for example consumer preferences and carbon emissions factors. As a consequence, the farther the time horizon of the policy analysis, the less likely it becomes that the world economy will be as given by the benchmark data. In particular, with respect to climate policy analysis, a standard CGE model represents a reduction in the use of fossil fuels by substitution of fossil fuel inputs by other inputs in the production structure. It does not represent investment in low-carbon technologies over time (like for example Leimbach et al. 2010).

3 Carbon content of trade

We calculate the implicit carbon contents of traded commodities using the GTAP 7 data set for 2004 (Narayanan and Walmsley 2008) in combination with emissions data computed from the GTAP 7 data set (Lee 2008).[7] Such implicit carbon contents capture

---

[6] Full technological catching up would be far beyond the time horizon of our analysis.

[7] For this section, we only need the GTAP 7 data set, not the CGE model itself. Like Peters and Hertwich (2008), we do not distinguish intermediate inputs by source country, since the GTAP data do not provide bilateral intermediate good flows. The GTAP 7 data apparently incorporate some inconsistencies between intermediate inputs in currency value terms and fossil fuel (emissions) inputs in physical value terms and differences in accounting emissions. For details see Peters and Hertwich (2008) and their supporting information. These inconsistencies can be relevant when computing sector or product specific results, ut probably not on the macro level. Therefore, the results should be treated

all emissions that occur during the production processes of commodities. Our calculation improves on Pan et al. (2008) by using the new GTAP 7 data and by distinguishing intermediate good inputs by country of origin (for detailed explanations see Ackerman et al. 2007). The latter aspect seems important for computing Chinese carbon contents of trade, since a substantial part of Chinese exports is produced by using imported intermediate goods (so that the value added is relatively low).

In the first step, we derive an input-output table, in other words a 90 × 90 Leontief technology matrix Λ, from the GTAP 7 data. In each column, it describes the production of a commodity i (in a sector i) in region r. The first columns contain all commodities i produced in the first region, the following columns contain all commodities produced in the second region and so on. Within each column, commodities i are listed in the same order representing the intermediate good inputs that are necessary to produce one output unit of commodity i in region r. At this point, the GTAP 7 data set does not provide *bilateral* trade flows of *intermediate* goods. It does, however, provide bilateral data on total trade flows μ (for intermediate input use plus consumption) and it does provide *bisectoral* data on total imported intermediate inputs ι of firms (without distinguishing by source country). Therefore, we use the following weighting algorithm to compute bilateral intermediate good flows ι^b from sector ii in region rr to sector i in region r:

$$\iota^b(rr, r, ii, i) = \iota(r, ii, i) \frac{\mu(rr, r, i)}{\sum^{rr} \mu(rr, r, i)} \tag{1}$$

The underlying assumption is that the distribution of source countries of imports is the same for intermediate good imports as for total imports.

In the second step, we compute the Leontief inverse χ containing the volumes of all commodities that are necessary to satisfy the demand for one unit of each commodity, and additionally to satisfy the need for intermediate inputs throughout all production stages. Herein, Ξ is a 90 × 90 identity matrix.

$$\chi = \Lambda \times \chi + \Xi \quad \Leftrightarrow \quad \chi = [\Xi - \Lambda]^{-1} \tag{2}$$

In the third step, we derive the direct emissions per unit of output i, denoted by the 1×90 vector ε. These direct emissions occur in each production stage via direct inputs of fossil fuels (coal, gas and oil).[8] For this purpose, we use the data on direct emissions that

---

with some caution.

[8] Assume, steal production uses electricity and burns oil when running machines. Then, only these direct emissions from burning oil are included at this stage of the calculation.

Lee (2008) computes from the GTAP 7 data. She takes into account that, depending on the region, a certain share of oil and gas goes into plastic products within the chemical sector. She also takes into account that the oil sector encompasses processes where oil inputs are not burned, but refined in order to gain improved oil products. In this case, she assumes that the resulting emissions are zero.

In the fourth step, we multiply ε with χ. As a result, we obtain the 1×90 carbon intensity vector ζ that contains the emissions over all intermediate production stages that occur when producing one unit of each commodity i in each region r.

$$\zeta = \varepsilon \times \chi \tag{3}$$

Figure 1 shows the results for the benchmark year 2004.[9] The figure illustrates that products from (mainland) China (CHI) have the highest carbon (CO_2) intensities (except transportation trn), on average about 3.1kg/US\$. Especially, the Chinese carbon content of electricity generation (egw) is extremely high due to the importance of inefficient coal power in (mainland) China.[10] As expected, commodities produced in the developing countries (DEV) have the second highest carbon contents, on average about 1.6kg/US\$, and commodities produced in the industrialized countries (IND) have the lowest carbon intensities, on average about 0.7kg/US\$.

In the fifth step, *total* carbon contents of *traded* commodities per year can easily be computed by multiplying the carbon intensity factors shown in Figure 1 by the related volumes of commodity trade. (Note that implicit carbon trade within regions is not included.) Figure 2 shows the results for exports of each region. As expected, the ranking of implicit Chinese carbon export volumes is similar to the ranking of commodity export volumes. The three highest and almost equal carbon volumes are embodied in exports of textiles, apparel and leather (tex); electrical equipment (elm) and machinery (mac). Chemicals, rubber and plastic (crp) contribute the fourth highest carbon export volume which is lower than the three highest volumes. All other products contribute lower

---

[9] We distinguish 30 sectors: agriculture and food (agr), textiles, apparel and leather (tex), beverages and tobacco (bev), business services (bui), chemicals, rubber and plastic (crp), culture and recreation (cus), coal (col), communication (com), construction (con), crude oil (cru), electricity supply (egw), electrical equipment (elm), ferrous metals (fem), financial intermediation (fin), gas (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 (oil), trade and wholesale (trd), public services (pub), real estate (ree), transport machinery (trm), transportation (trn), water supply (wat), wood (woo).

[10] The emissions intensity of gas in (mainland) China was obviously an outlier. Therefore, we assumed it is equal to the emissions intensity of gas in developing countries. For further comments on accounting problems in the GTAP data see Peters and Hertwich (2008) and their supporting information.

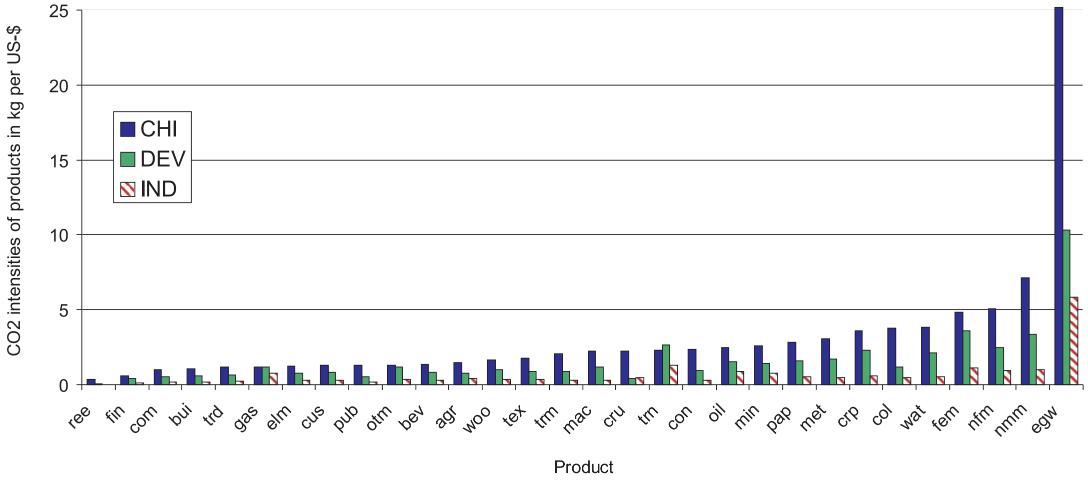

Figure 1: Carbon intensity factors of products

carbon export volumes. The other developing countries obviously export substantial carbon volumes via transportation services (trn);[11] non-ferrous (nfm) and ferrous (fem) metals; via agricultural and food products (agr); via crude oil (cru); and via petroleum and coal products (oil).

Figure 3 illustrates the result of summing up over carbon contents of traded commodities per region for the benchmark year 2004. The triangle in Figure 3 visualizes the total quantities of CO_2 in Gt (Giga tons) that are implicitly traded between regions. While about 1.6Gt flow from the developing countries to the industrialized countries, (mainland) China alone exports about 1.1Gt to the industrialized countries. CO_2 exports from the industrialized region to the developing region and China, as well as CO_2 flows from the developing region to (mainland) China and vice versa, are relatively low. Figure 3 does not show implicit carbon trade *within* regions. The implicit carbon trade within the industrialized region (between industrialized countries) is substantial; it amounts to 2.7Gt. The implicit carbon trade within the developing region amounts to 0.7Gt.

The percentage numbers show net CO_2 exports (implicit CO_2 exports minus imports) relative to total emissions that are actually generated in each region. As expected, China is a major net carbon exporter (24% of total Chinese emissions), while the industrialized region is a net carbon importer (15% of total emissions). The developing region is a net

---

[11] The high volume of carbon exports via transportation services stems from the high export volume of transportation services given by the GTAP 7 data.

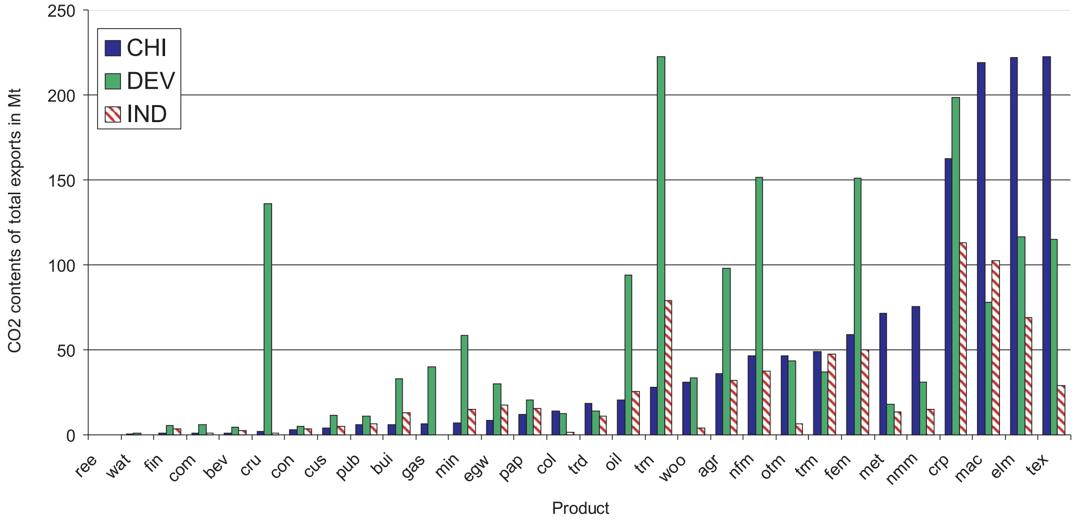

Figure 2: Implicit carbon contents of exported products

carbon exporter as well (12% total emissions).[12]

These outcomes suggest that climate policy in the industrialized region alone might cause carbon leakage: Production might increase in developing countries such as China as a response, and trade of carbon intensive commodities to the industrialized region might increase. Therefore, it seems worthwhile to examine the effectiveness of policies that might lower implicit carbon trade, in particular carbon based tariffs.

4 Carbon tariffs

This section uses the carbon intensities of commodities computed in the previous section to set carbon content based tariffs on imports from a region without a carbon price, in particular China, to a region with a carbon price under a Contraction and Convergence policy (C&C, introduced by GCE 1990).[13]

---

[12] Compared with Peters and Hertwich (2008) who calculate the carbon contents of trade based on GTAP 6 for the year 2001, implicit carbon carbon exports of China have risen from 0.8Gt (24.4% of total Chinese emissions) in 2001 to 1.4Gt (31.3%) in 2004. Relative carbon imports of China have risen from 0.2Gt (6.6%) to 0.3Gt (7.7%). Thus, net carbon exports of China have risen from 0.6 (17.8%) to 1.1Gt (23.6% $\approx$ 24%). According to Pan et al. (2008), China's net CO_2 exports amount to 1.7Gt in the year 2006.

[13] Herein, on the one hand, we neglect the following aspect: Part of intermediate goods used in Chinese production are imported and thus have been subject to a carbon tax in the region of origin. Under a carbon tariff, Chinese exports are taxed again based on their full carbon content. Deducting these carbon taxes already paid would reduce the effect of the border tax adjustment under scrutiny. On the other hand, the emissions data for GTAP 7 (Lee 2008) yield relatively low emissions for China. In this respect, a carbon tariff would have a stronger effect if Chinese emissions were higher.

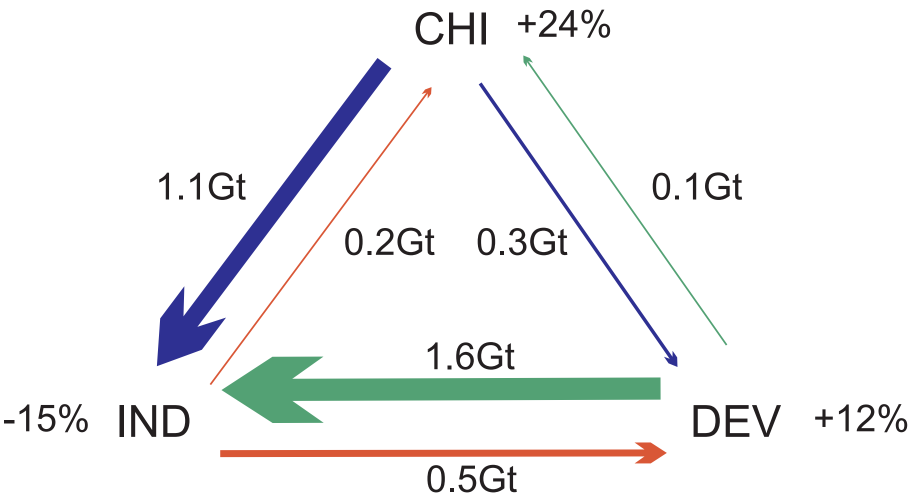

Figure 3: Interregional carbon contents of trade

C&C has been frequently suggested in the scientific and political debate. It treats all people in all countries equally with respect to emissions and it favors high-population countries and poor countries hat have today much lower per capita emissions than the industrialized countries. Therefore, it has a realistic chance of being accepted by the developing countries and of becoming implemented on a global scale. It appears interesting in particular with respect to China to analyze such a C&C policy. In mathematical terms, the endowment with emissions permits for region r at time or year t follows the rule (Peterson and Klepper 2007):

$$\theta^{CO_2}(t,r) = \theta^{CO_2}(2012,r)\frac{2050-t}{37} + \theta^{CO_2}(2050)\frac{t-2013}{37}, \quad \forall t \geq 2013 \tag{4}$$

Regional emissions in 2012, denoted by $\theta^{CO_2}(2012,r)$, are derived from the solution of the CGE for 2012. The global emissions level in 2050 is set exogenously to about 18.3Gt CO_2 which corresponds roughly to a 450ppm CO_2 intensity target (compare IPCC 2001). As a result, per capita emissions converge step by step from their regionally different levels in 2012 to an equalized level of 2t per capita in 2050. Given these regional permit endowments, permits can be traded across regions and across all sectors, yielding efficient emissions reductions in the participating regions.

In the next step, we examine carbon based tariffs on imports from a region without a carbon price to a region with a carbon price. The political debate also includes carbon tax rebates on exports from a region with a carbon price to a region without a carbon price. The latter is especially discussed with respect to competitiveness and fairness aspects concerning exporters that face a carbon price, while their foreign rivals do not.[14] In our border tax adjustment (BTA) experiments, the carbon based ad valorem tariff rate $\tau^{BTA}(t, rr, r, i)$ is endogenously adjusted, where rr denotes exporting regions (for example CHI) outside the regime, and r denotes importing regions within the regime (for example IND), and i denotes sectors or commodities. In the absence of the first best solution, a carbon price in all sectors in all regions, we aim at a second best solution by pricing imports as if they had been produced domestically. The tax rate depends on the carbon intensities of commodities in the exporting region, denoted by $\zeta(rr, i)$. This implies that policy makers exactly know the real implicit carbon contents of the imported products, at least in the benchmark year. Furthermore, the tariff rate depends on the current carbon price $p^{CO_2}(t)$ and on the current (Armington composite) import price of the commodity $p^M(t, r, i)$. The border tax adjustment is then given by the following constraint:[15]

$$\tau^{BTA}(t, rr, r, i) = \frac{p^{CO_2}(t)}{p^M(t, r, i)}\zeta(rr, i) \tag{5}$$

Thus, imports of commodities are due to the same carbon tax as the corresponding domestically produced commodities. As a result, across sectors, the carbon based tax rate is mainly determined by the carbon intensity. Over time, it basically follows the development of the carbon price.

In the next step, we distinguish two technology scenarios (for a detailed description see Hübler 2011): In scenario *green*, we assume exogenous energy efficiency gains of 1% per year in all regions. We assume total factor productivity gains of 0.5% per year in China (CHI), 1.3% in the developing region (DEV) and 0.86% in the industrialized region (IND). In CHI, we additionally assume energy efficiency and total factor productivity gains via international technology diffusion associated with imports and FDI inflows. The resulting time paths of CO_2 emissions come close to the Alternative Policy Scenario by IEA (2007) and are optimistic regarding CHI's future business as usual

---

[14] Pauwelyn (2007), for example, notes: "Such competitiveness provisions would essentially aim at leveling the playing field by imposing the same or similar costs on imports, as US federal climate policy imposes on domestic US production. To level the playing field on world markets, US exports could also be exempted from domestic climate restrictions." For further details see Houser et al. (2008). Moreover, Meade (1974) and Grossman (1980) show under which conditions an equal border tax on all imports and a corresponding subsidy on all exports lead to a readjustment of the exchange rate without real economic effects. In our current analysis with import tariffs at different rates but no export subsidies, these criteria are not fulfilled.

[15] Re-arranging the equation and multiplying by the volume of imports $M(t, r, i)$ yields: $M(t, r, i) \cdot p^M(t, r, i) \cdot \tau^{BTA}(t, rr, r, i) = M(t, r, i) \cdot \zeta(rr, i) \cdot p^{CO_2}(t)$. Now, the left hand side is the total tax to be paid for importing commodity i into region r, given the ad valorem tax rate $\tau^{BTA}(t, rr, r, i)$. The right hand side computes the carbon content of commodity i and prices it at the current carbon price.

(BAU) emissions intensity.

In scenario *brown*, we do not assume any energy specific efficiency gains in any region. We do not assume energy efficiency or total factor productivity gains associated with imports or FDI inflows, either. We assume total factor productivity gains of 2% per year in China (CHI), and 1.3% in the developing region (DEV) and 0.86% in the industrialized region (IND) as before. The resulting time paths of CO_2 emissions come close to the High Growth Scenario by IEA (2007). They are more pessimistic regarding future emissions intensities, especially of CHI. In this scenario, the Chinese economy also strongly grows towards the end of the time horizon in 2030 and thus produces high emissions.

The BAU emissions paths for scenarios *green* and *brown* and the emissions paths resulting from the policy experiments, explained in the following, are illustrated in Figure 4. Obviously, DEV grows strongly and overtakes IND at the end of the time horizon with respect to emissions. While CHI's emissions grow moderately in scenario *green*, they come close to those of IND and DEV in scenario *brown*.

We then analyze several policy scenarios for each technology scenario. Herein, a "+" before a region's name indicates that this region is included in the climate policy regime, a "-" indicates that it is not. +bta indicates that border tax adjustment is imposed on imports from regions outside the climate policy regime to regions within the climate policy regime.

Figure 4 illustrates the emissions paths under the different technology and policy scenarios. (Scenario +chi-dev+ind is not shown.) In "bau", there is no climate policy in any region, while in "pol", climate policy covers all regions. Obviously, the inclusion of regions to the Contraction and Convergence (C&C) regime reduces emissions substantially. Border tax adjustments on imports (+bta), on the contrary, show small impacts on CHI's emissions, while the impact on DEV's and IND's emissions is hardly visible in the figure, since it is so small.

Nevertheless, BTA tax rates reach substantial values. In scenario -chi+dev+ind+bta *green*, the carbon based tariff rate $\tau^{BTA}(2013, CHI, IND, i)$ varies between 0.07% for real estate; 0.2% for communication, public services and others; and almost 6% for gas and electricity. According to this scenario, the CO_2 price will rise up to 65 US-$ per ton of CO_2 in 2030. As a consequence, the carbon based tariff rate will vary between 2% for real estate; around 30% for paper, oil and metal products; more than 40% for chemicals and water; around 50% for coal; more than 60% for ferrous and non-ferrous metals; almost 80% for non-metallic mineral products; and 265% for electricity, given

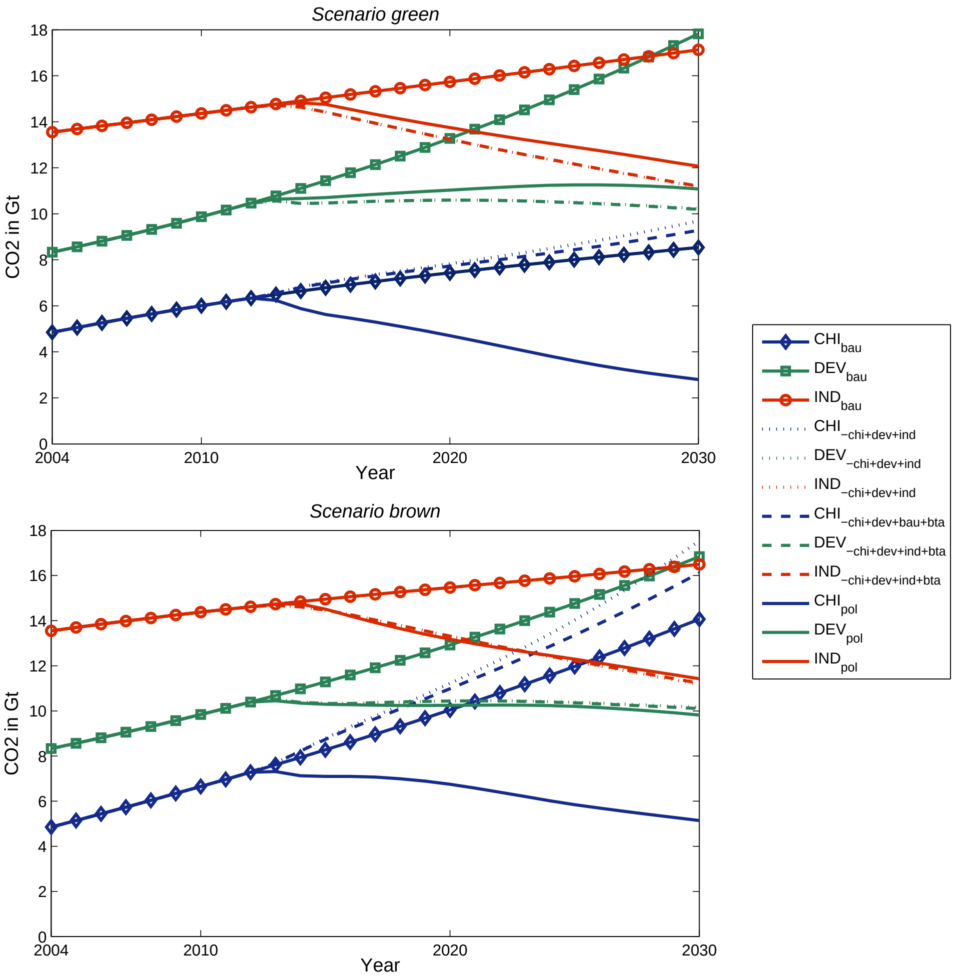

Figure 4: Time paths of regional CO_2 emissions under scenarios *green* and *brown*

that China's energy supply will still strongly rely on coal.[16]

`- Table 1 about here -`

`- Table 2 about here -`

Tables 1 and 2 describe the technology and policy scenarios in detail. Several aspects are important for the interpretation of the results:

First, our C&C scenario reduces per capita emissions from their 2012 levels to equal regional levels of about 2t of CO_2 in 2050. We do not consider a scenario, where global

---

[16] Again, the Chinese gas sector appears as an outlier; the related border tax rate would be about 365%.

emissions must not exceed a certain level in order to meet a certain CO_2 concentration or a temperature target, such as the 2 degree target. The latter would require that regions within the regime cut emissions to a larger extent the more countries are outside the regime that do not reduce emissions.[17] As a consequence of our scenario assumption, global emissions cuts will be insufficient to reach an ambitious temperature target, if not *all* regions are "in the boat".

Second, the inclusion of a region into C&C implies that firms in this region have an incentive to use less fossil fuel inputs for production in order to reduce their emissions intensity of production and hence their tax payments. BTA policies, on the contrary, do not create such an incentive, since the actual inputs of firms cannot be measured. They simply imply a punishment for exporting emissions intensive products based on benchmark data. As a consequence, imports will shift from high-carbon to low-carbon products, and imports will decline in total as well. The difference is that the former policy is an input tax at a fixed rate for each fossil fuel inputs (coal, gas and oil), while the latter is an output tax at a fixed rate for each commodity (metal products, chemical products and so forth).

Third, the regional aggregation is large (except China, which is the focus of our analysis). Therefore, we cannot disentangle how certain countries with different characteristics are affected; for example least developed countries such as Ethiopia, fast-growing high-population economies such as India, or oil exporters such as Saudi Arabia – which are all merged in region DEV. As a consequence, high-population countries within region DEV benefit from the *per capita* based C&C policy, while oil exporters suffer from climate policy. The overall effect of a C&C policy for region DEV is therefore ambiguous. The aim of this aggregation is, however, to contrast the effects for China with those for OECD countries and those for the rest of the world without tumbling over numerous country specific effects. Furthermore, an impact of a certain size in absolute terms, for example a tax revenue through border tax adjustment, has a higher *relative* impact on CHI than on IND and DEV due to CHI's smaller economic size.

Fourth, a long-term policy analysis is sensitive to the time horizon under scrutiny. Since regions CHI and DEV are supposed to achieve sustained long-run growth, while emissions targets will become more stringent in the long-run, climate policy will hit these region harder the longer the time horizon. Moreover, as explained in section 2, a numerical model is determined by the benchmark year data, for example with respect to

---

[17] This can result in more or less infeasible situations, if too less countries are in the regime, so that the burden for the countries within the regime becomes too heavy.

energy and emissions intensities of production. Therefore, uncertainty rises, the longer the time horizon. Taking this into account, we have chosen 2030 as a medium-term compromise. Since assumptions on technical progress play a major role for the results, we contrast two technology scenarios.

Keeping in mind the assumptions and caveats above as well as those explained at the end of section 2, we can now examine the simulation results reported in Table 1 and Table 2.

Welfare and terms of trade. We measure welfare effects as the Hicks-equivalent Variation between a policy scenario and BAU (relative to households' expenditures in BAU), cumulated from 2004 until 2030 and discounted at a rate of 2% per year. As a result, in technology scenario *green*, under all policies without BTA, CHI is at least equally off as in BAU. The exact reason is difficult to separate in a complex CGE. Nevertheless, a look at the terms of trade gives a hint: The terms of trade (in 2030 relative to the 2004 value set to 1) are in all policy scenarios without BTA higher than in BAU. Accordingly, fossil resource prices, and prices of goods that CHI uses as intermediate inputs, fall relative to the prices of commodities that CHI exports. Moreover, in scenario *green* that is optimistic with respect to CHI's emissions intensity, CHI becomes a permit seller and benefits from the related revenues. In this sense, it is better for CHI, when more countries join the C&C regime that buy CHI's permits. CHI's permit sales are also beneficial for the other regions – but only to a very small extent. A possible reason is that CHI's exports become more expensive, as indicated by the terms of trade. This terms of trade effect is disadvantageous for the other regions that import CHI's products, and counteracts the efficiency gains with respect to emissions permits trade.

In both technology scenarios, *green* and *brown*, CHI achieves the highest welfare improvement if it stays outside the regime, while the rest of the world is inside. This implies that terms of trade improvements and leakage effects are higher than CHI's benefits from participating in the permit market. The inclusion of DEV into the regime causes a welfare loss of around 1% compared with BAU for DEV, while the inclusion of IND creates only a small welfare loss for IND. Apparently, the disadvantages of climate policy for fast growing economies and for oil exporters within DEV dominate. The introduction of BTA, however, causes a substantial drop in the terms of trade and in welfare of the targeted region, in particular a welfare loss of 1 to 2 % for CHI.

However, the picture looks partly different in technology scenario *brown*. On the one hand, BTA has similar effects as before. On the other hand, the inclusion of CHI into the regime causes a welfare loss of around 1% compared with BAU for CHI, similar to the welfare loss for DEV, which becomes stronger in *brown* than in *green.* Different to scenario *green*, DEV does not benefit from the inclusion of CHI, possibly because CHI does now buy permits from the market instead of selling permits. In summary, whether CHI looses or gains from joining the regime compared with BAU depends on the technology scenario. But in both scenarios, CHI looses when joining the regime compared with the situation, where CHI is excluded, but all other regions are included (-chi+dev+ind), since CHI can benefit from leakage effects in the latter case.

In summary, we find the following important result regarding welfare effects that holds in both technology scenarios: When China does not participate in the regime and instead a carbon tariff is imposed on its exports, it will likely be worse off than when participating. This result does not necessarily hold for the developing region in general.

Emissions and energy intensity. The exclusion of CHI from the policy regime, while the rest of the world is included (-chi+dev+ind), creates an increase in CHI's emissions of about 5% in *green* and about 11% in *brown.* Similarly, the exclusion of DEV, while the rest of the world is included (+chi-dev+ind), creates an increase in DEV's emissions of about 8% in *green* and about 15% in *brown.* These findings indicate substantial carbon leakage effects. CHI's or DEV's energy intensities strongly improve compared with BAU when they are "in the policy boat", while it worsens compared with BAU when they are not. Obviously, BTA policies with fixed tax rates on produced commodities, achieve only small improvements in energy intensity and emissions reductions. Emissions reductions are around 1 to 2% in each region, CHI and DEV, and are thus smaller than the leakage effects that we observed.

Interestingly, the implicit inter-regional CO_2 flows computed in the previous section are almost as high as the explicit CO_2 flows through permit trading in 2030 that we find here. In both cases, IND imports around 2 to 3Gt of CO_2 a year from CHI and IND. Herein, CHI's supply or demand of permits strongly depends on CHI's technical progress, in our case expressed by the two technology scenarios, as discussed above.

5 Conclusion

In the first step, we calculate implicit carbon flows through commodity trade between an industrialized region, a developing region, and mainland China, based on the GTAP 7 data for 2004. We find substantial implicit carbon flows from China and the developing region to the industrialized region, in accordance with the literature. Most of China's implicit carbon exports occur through textiles, apparel and leather; electrical equipment; and machinery. Our findings indicate the possibility of carbon leakage effects, which are confirmed by our computable general equilibrium analysis. Moreover, we compute carbon intensity factors of all commodities. While we are able to compute these carbon intensity factors accurately given the data, in real policy, data availability and accuracy can be a difficulty when calculating carbon contents of products from certain countries.

In the second step, we analyze carbon tariffs by applying the carbon intensity factors of commodities that we computed in the first step, to our computable general equilibrium model. The resulting carbon content based tariffs are imposed on imports from a region that is not part of a global post-Kyoto Contraction and Convergence regime (GCE 1990), in particular China or the region of the other developing countries, to a region that is part of the regime.

We find as a main result: When China does not participate in the regime and instead a carbon tariff is imposed on its exports, it will likely be worse off than when participating. This result does not necessarily hold for the developing region in general. Therefore, carbon based tariffs might encourage China to join a Contraction and Convergence policy regime, but they might not necessarily encourage developing countries in general. The reason is probably that the Chinese economy is carbon intensive as well as export intensive. In this case, a carbon tariff might be a threat – in case of other developing countries it might not be a threat. Moreover, we find relatively small carbon emission reductions stemming from the introduction of carbon tariffs. This result casts doubt on the effectiveness of carbon tariffs as a direct measure for emission reductions.

A main reason for the small emissions reductions found in the analysis is probably that such carbon tariffs are imposed on commodities based on base year carbon contents that are fixed over time, and not directly on fossil fuel inputs. This cancels firms' incentive to reduce fossil fuel inputs. Another reason is probably that China's exports are responsible for about one quarter of total Chinese emissions so that three quarters of emissions are unaffected.

In order to address the first reason, carbon intensity factors would need to be measured and adjusted simultaneously in order to create a better incentive for emissions reduction via tariffs. But this would require Chinese firms to provide exact information on their energy inputs (or emissions outputs) regularly to European, US and other policy makers. This requirement does not appear as a feasible option.

The alternative assumption under discussion is that carbon intensity factors of imported products from different countries are homogenous and equal to the carbon intensity factor of the corresponding domestically produced products in the importing country. This policy, however, discriminates against exporters with low carbon intensities and benefits exporters with high carbon intensities. And due to on average lower emissions intensities of importing high-income countries compared with low-income exporting countries, the effects of border tax adjustment would be lower than in our analysis based on exporters' carbon intensities.

Therefore, the full inclusion of China into a global post-Kyoto regime appears to be more effective with respect to emissions reductions than the introduction of carbon tariffs. Whether China significantly looses or slightly gains from the inclusion into the climate regime compared with business as usual depends on the strength of (energy saving) technical progress. Independent of the assumptions on technical progress, China achieves the highest welfare gain when it is excluded from climate policy while all other countries are included, since it can then benefit from leakage effects. The industrialized and developing region seem not to benefit much from China's inclusion into this policy regime, or even slightly loose in case of the developing countries. A probable reason is that the introduction of a carbon price in China raises the price of Chinese commodities which the other countries, especially the industrialized countries, import at a large scale. Herein it is important to note that in our policy scenario all regions follow the same emissions targets, no matter China joins the regime or not. Therefore, global emissions will be drastically higher, if China does not join the regime. In this sense, it is still in the interest of all countries that China is "in the boat" in order to reduce global climate change damages. But possibly the full inclusion of developing countries such as China is not yet feasible.

Hence, the following carbon tariff policy could ba a feasible compromise with respect to Chinese exports: Carbon intensity factors are estimated (on a rough sectoral base) and updated after a certain period of time (for instance after five years) when changes in the emissions intensity can be measured and proven. This will take emissions intensity improvements of exporting economies like China on a macro level into account, without large bureaucratic efforts to measure and verify carbon emissions of single firms continuously. It would create an incentive for governments to foster energy and emissions saving policies such as in the Chinese Five Years Plan.

Future research may explicitly model endogenous technological progress including the rising share of renewable energies and possibly CCS (carbon capture and storage) since the deployment of new technologies strongly effects future emissions paths and since coal power plays a major role in China. It might turn out that international transfer of low carbon energy technologies is a more promising option than imposing trade barriers for successfully dealing with climate change.

6 References

Ackerman, F., M. Ishikawab and M. Suga (2007). The carbon content of Japan-US trade. Energy Policy 35, 4455-4462.

Alexeeva-Talebi, V., A. Löschel and T. Mennel (2008a). Climate Policy and the Problem of Competitiveness: Border Tax Adjustments or Integrated Emission Trading? ZEW Discussion Paper No. 08-061, 33 pp.

Alexeeva-Talebi, V., N. Anger and A. Löschel (2008b). Alleviating Adverse Implications of EU Climate Policy on Competitiveness: The Case for Border Tax Adjustments or the Clean Development Mechanism? ZEW Discussion Paper No. 08-095, 26 pp.

Babiker, M.H. and T. F. Rutherford (2005). The Economic Effects of Border Measures in Subglobal Climate Agreements. Energy Journal 26(4), 99-126.

Bhagwati, J. and P. C. Mavroidis (2007). Is action against US exports for failure to sign Kyoto Protocol WTO-legal? World Trade Review 6(2), 299-310.

Böhringer, C., Fischer, C. and K.E. Rosendahl (2010). The Global Effects of Subglobal Climate Policies. The B.E. Journal of Economic Analysis & Policy 10(2), 13.

Broder, J. M. (2009). Obama Opposes Trade Sanctions in Climate Bill. The New York Times, June, 28, 2009, online article:
$http://www.nytimes.com/2009/06/29/us/politics/29climate.html?_r = 1.$

China Statistical Yearbook (2006, 2007). National Bureau of Statistics of China, China Statistics Press, online access:
http://www.stats.gov.cn/english/statisticaldata/yearlydata/.

Friedman, L. (2009). Possible Plan for Tariffs on Imports From China Remains Alive in House Climate Bill. The New York Times, June, 24, 2009, online article:
http://www.nytimes.com/cwire/2009/06/24/24climatewire − possible − plan − for − tariffs − on − imports − from − ch − 25103.html.

GCI (1990). Contraction and Convergence (C&C) is the science-based, global climate policy framework proposed to the UN since 1990 by the Global Commons Institute,
http://www.gci.org.uk/.

Grossman, G. M. (1974). Border-Tax Adjustments - Do they distort trade? Journal of International Economics 10, 117-128.

Hall, R. E. and C. I. Jones (1999). Why do some countries produce so much more output than others? Quarterly Journal of Economics 114 (1), 83-116.

Hilderink, H. B. M. (2000). PHOENIX plus: the population user support system version 1.0, online information:
$http : //www.mnp.nl/en/themasites/phoenix/index.html.$

Houser, T., Bradley, R., Childs, B., Werksman, J. and Heilmayr, R. (2008). Leveling the Carbon Playing Field. International Competition and Climate Policy Design. Peterson Institute for International Economics and the World Resource Institute, Washington, DC, USA, 95 pp.

Hübler, M. (2011). Technology Diffusion under Contraction and Convergence: A CGE Analysis of China. Energy Economics 33(1), 131-142.

IEA (2006). World Energy Outlook. International Energy Agency, Paris, France, 601 pp.

IEA (2007). World Energy Outlook: China and India Insights. International Energy Agency, Paris, France, 674 pp.

IPCC (2001). Synthesis Report - Summary for Policymakers. In: Climate Change 2001. Third Assessment Report of the Intergovernmental Panel on Climate Change, 34 pp.

IPCC (2007). Mitigation from a cross-sectoral perspective. In: Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, UK and New York, NY, USA, 72 pp.

Klepper, G. and K. Springer (2000). Benchmarking the Future: A Dynamic, Multi-Regional, Multi-Sectoral Trade Model for the Analysis of Climate Policies. Kiel Working Paper No. 976, 72 pp.

Klepper, G., S. Peterson and K. Springer (2003). DART97: A Description of the Multi-regional, Multi-sectoral Trade Model for the Analysis of Climate Policies. Kiel Working Paper No. 1149, 40 pp.

Krugman, P. (2009). The WTO is making sense. The New York Times, June, 26, 2009, online article:
$http : //krugman.blogs.nytimes.com/2009/06/26/the - wto - is - making - sense/.$

Lee, H.-L. (2008). An Emissions Data Base for Integrated Assessment of Climate Change Policy Using GTAP. GTAP Resource #1143, GTAP CO_2 emissions (for V7), online access:
$https : //www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID = 1143.$

Leimbach, M., N. Bauer, L. Baumstark and O. Edenhofer (2010). Mitigation Costs in a Globalized World: Climate Policy Analysis with REMIND-R. Forthcoming in: Environmental Modeling and Assessment 15(3), 155-173.

Lessmann, K., R. Marschinski and O. Edenhofer (2009). The effects of tariffs on coalition formation in a dynamic global warming game. Economic Modelling 26, 641-649.

Liu, X. and C. Wang (2009). Quantitative analysis of CO_2 embodiment in international trade: An overview of emerging literatures. Frontiers of Environmental Science and Engineering in China 3(1), 12-19.

Manders, T. and P. Veenendaal (2008). Border tax adjustments and the EU-ETS - A quantitative assessment. CPB Document No. 171, 36 pp.

Meade, J. E. (1974). A Note on Border-Tax Adjustment. Journal of Political Economy 82(5), 1013-1015.

NBS (2006). InputOutput Tables of China in 2002. National Bureau of Statistics, Beijing, China Statistic Press.

Narayanan, B. G. and T. L. Walmsley (eds.) (2008). Global Trade, Assistance, and Production: The GTAP 7 Data Base. Center for Global Trade Analysis, Purdue University, online information:
$https://www.gtap.agecon.purdue.edu/$.

OECD (2008). Environmental Outlook to 2030. Paris, France, 523 pp.

Pan, J., J. Phillips and Y. Chen (2008). China's balance of emissions embodied in trade: approaches to measurement and allocating international responsibility. Oxford Review of Economic Policy 24(2), 354-376.

Pauwelyn, J. (2007). U.S. Federal Climate Policy and Competitiveness Concerns: The Limits and Options of International Trade Law. Prepared by the Nicholas Institute for Environmental Policy Solutions, Duke University, Washington, DC, USA, 45 pp.

Peters, P. and E. G. Hertwich (2008). CO_2 Embodied in International Trade with Implications for Global Climate Policy. Environmental Science and Technology, 42(5), 1401-1407, online access to the article and to supporting information:
$http://pubs.acs.org/doi/suppl/10.1021/es072023k$.

Peterson, S. and G. Klepper (2007). Distribution Matters - Taxes vs. Emissions Trading in Post Kyoto Climate Regimes. Kiel Working Paper No. 1380, 26 pp.

Shui, B., and R. C. Harriss (2006). The Role of CO_2 Embodiment in US-China Trade. Energy Policy 34, 4063-4068.

Sijm, J. P. M., O. J. Kuik, M. Patel, V. Oikonomou, E. Worrell, P. Lako, E. Annevelink, G. J. Nabuurs and H. W. Elbersen (2004). Spillovers of Climate Policy - An assessment of the incidence of carbon leakage and induced technological change due to CO_2 abatement measures. Netherlands Research Programme on Climate Change Scientific Assessment and Policy Analysis, 251 pp.

Springer, K. (2002). Climate Policy in a Globalizing World. Springer, Berlin, Heidelberg, New York, 293 pp.

Tseng, W. and H. Zebregs (2002). Foreign Direct Investment in China: Some Lessons for other Countries. In: W. Tseng and M. Rodlauer (eds.), China Competing in the Global Economy, IMF, 68-104.

Whalley, John and X. Xin (2006). Chinas's FDI and Non-FDI Economies and the Sustainability of Future High Chinese Growth. NBER Working Paper No. 12249, 24 pp.

Wiedmann, T., M. Lenzen, K. Turner and J. Barrett (2007). Examining the Global Environmental Impact of Regional Consumption Activities, Part 2: Review of Input-Output Models fort the Assessment of Environmental Impacts Embodied in Trade. Ecological Economics 61, 15-26.

7 Appendix

This section contains key equations of the CGE model. For further details and data sources see Klepper and Springer (2000), Springer (2002), Klepper et al. (2003) and Hübler (2011). Tables 1 and 2 explain the meaning of the parameters and variables.[18] The equations are written in quantities, while all prices are endogenous.

Cumulated, discounted welfare effect excluding climate change damage is derived from the relative Hicks-equivalent variation of policy scenario 1 compared with reference scenario 0:

$$W(r) = \frac{\sum_{t=2004}^{2025}\{P[p^C(2004,r),U^1(t,r)] - P[p^C(2004,r),U^0(t,r)]\}(1-\rho)^{(t-2004)}}{\sum_{t=2004}^{2025} P[p^C(2004,r),U^0(t,r)](1-\rho)^{(t-2004)}} \tag{6}$$

Households equate expenditure to income:

$$p^C C = p^K K + p^L L + p^B B + p^{CO_2} EM + R(.), \quad \forall (t,r) \tag{7}$$

Capital accumulation with a constant depreciation rate and saving rate:

$$K(t+1,r) = [1-\delta(r)]K(t,r) + \sigma(r)Y(t,r) \tag{8}$$

Splitting capital supply in IND into domestic use and FDI to CHI:

$$K(t,IND) = cet[\tilde{K}(t,IND), F(t,CHI)] \tag{9}$$

Exogenous labor augmentation (via population growth and educational improvements):

$$L(t+1,r) = [1+\lambda(t,r)]L(t,r) \tag{10}$$

---

[18] The 30 production sectors are listed as a footnote in section 3.

Basic production structure (producers minimize costs taking input and output taxes $\tau^{(\cdot)}$ into account):

$$cet(D, X) = ltf\langle N, ces\{B, cd[\tilde{K}, L, E]\}\rangle, \quad \forall(t, r, i), r \in \{IND, DEV\} \tag{11}$$

Basic production structure in China (producers minimize costs taking input and output taxes $\tau^{(\cdot)}$ into account):

$$cet(D, X) = ltf\langle N, ces\{B, cd[cd(\tilde{K}, F), L, E]\}\rangle, \quad \forall(t, CHI, i) \tag{12}$$

Imported and domestically bought commodities form a consumption bundle:

$$C(t, r) = ces[D(t, r, i), M(t, r, i)] \tag{13}$$

Linking CO_2 emissions to fossil fuels (col, gas, oil) in an energy bundle:

$$E = cd\{cru, egw, ltf[EM(e), e]\}, \quad \forall(t, r) \tag{14}$$

Armington aggregation of imports from different regions (where export subsidies, and carbon and non-carbon based import tariffs $\tau^{(\cdot)}$ are imposed on traded commodities):

$$M(t, r, i) = ces\{ltf[X(t, rr, r, i), \Upsilon(rr, r, i)]\} \tag{15}$$

Exogenous total factor productivity improvement:

$$A(t+1, r, i) = [1 + \vartheta^A(r)]A(t, r, i), \quad \forall r \in \{IND, DEV\} \tag{16}$$

Exogenous and endogenous total factor productivity improvement in China:

$$A(t+1, CHI, i) = [1 + \vartheta^A(r) + T^A(t, i)]A(t, CHI, i) \tag{17}$$

Exogenous energy efficiency improvement:

$$E(t+1, r, i) = [1 - \vartheta^E(r)]E(t, r, i), \quad \forall r \in \{IND, DEV\} \tag{18}$$

Exogenous and endogenous energy efficiency improvement in China:

$$E(t+1, CHI, i) = [1 - \vartheta^E(CHI) - T^E(t, i)]E(t, CHI, i) \tag{19}$$

Herein, the strength of total factor productivity improvements in China increases with the intensities of foreign capital, of vertical linkages within the production chain, of imports, and with the distance to the technology frontier:

$$T^A(t,i) = f[FI(t,i), VI(t,i), MI(t,i)][Y_L(t,IND,i) - Y_L(t,CHI,i)] \tag{20}$$

The strength of energy efficiency improvements increases with the same factors:

$$T^E(t,i) = f[FI(t,i), VI(t,i), MI(t,i)][Y_E(t,IND,i) - Y_E(t,CHI,i)] \tag{21}$$

Table 1: Economic indicators of scenario *green* (to be inserted in the main text)

Region	**CHI**	**DEV**	**IND**	**World**	**CHI**	**DEV**	**IND**	**World**
Policy		bau = -chi-dev-ind						
GDP 2030 (bill. 2004-US-$)	6594	15069	49327	70991				
CO$_2$ emissions 2030 (Gt)	8.54	17.82	17.13	43.49				
Energy productivity 2030 wrt. 2004	1.79	1.38	1.31	1.37				
Terms of trade 2030 wrt. 2004	0.86	1.11	1.00	-				
Policy		-chi-dev+ind				-chi-dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**0.14%**	**-0.29%**	**-0.19%**	**-**	**-1.38%**	**-0.95%**	**0.04%**	**-**
CO$_2$ emissions 2004-2030 wrt. bau	**1.88%**	**8.96%**	**-17.96%**	**-11.24%**	**1.11%**	**7.79%**	**-17.96%**	**-12.92%**
GDP 2030 (bill. 2004-US-$)	6552	14713	49088	70354	5366	12764	49045	67176
CO$_2$ emissions 2030 (Gt)	8.75	20.93	8.92	38.60	8.58	20.38	8.92	37.87
CO$_2$ price 2030 (2004-US-$ per t)	-	-	-	79.12	-	-	-	85.50
Energy productivity 2030 wrt. 2004	1.73	1.23	1.74	1.63	1.72	1.25	1.72	1.63
Terms of trade 2030 wrt. 2004	0.87	1.04	1.02	-	0.78	1.00	1.01	-
Policy		-chi+dev+ind				-chi+dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**0.41%**	**-1.11%**	**-0.03%**	**-**	**-1.42%**	**-1.00%**	**0.09%**	**-**
CO$_2$ emissions 2004-2030 wrt. bau	**5.09%**	**-18.97%**	**-13.07%**	**-28.53%**	**3.52%**	**-19.02%**	**-13.03%**	**-29.46%**
GDP 2030 (bill. 2004-US-$)	6600	14621	49143	70365	5492	14579	49128	69199
CO$_2$ emissions 2030 (Gt)	9.69	10.22	11.17	31.08	9.28	10.19	11.20	30.68
CO$_2$ sales 2030 (Gt)		2.26	-2.26	0		2.29	-2.29	0
CO$_2$ price 2030 (2004-US-$ per t)	-	-	-	63.22	-	-	-	65.06
Energy productivity 2030 wrt. 2004	1.54	1.78	1.50	1.56	1.57	1.79	1.50	1.56
Terms of trade 2030 wrt. 2004	0.89	0.97	1.03	-	0.76	0.96	1.03	-
Policy		+chi-dev+ind				+chi-dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**0.00%**	**-0.25%**	**-0.13%**	**-**	**0.22%**	**-0.83%**	**-0.04%**	**-**
CO$_2$ emissions 2004-2030 wrt. bau	**-30.67%**	**8.60%**	**-13.18%**	**-21.08%**	**-30.95%**	**7.45%**	**-13.05%**	**-22.36%**
GDP 2030 (bill. 2004-US-$)	6805	14804	49177	70786	6828	13532	49170	69529
CO$_2$ emissions 2030 (Gt)	2.72	20.86	10.75	34.32	2.67	20.30	10.80	33.76
CO$_2$ sales 2030 (Gt)	1.83		-1.83	0	1.88		-1.88	0
CO$_2$ price 2030 (2004-US-$ per t)	-	-	-	50.87	-	-	-	54.21
Energy productivity 2030 wrt. 2004	2.67	1.24	1.57	1.61	2.68	1.26	1.55	1.61
Terms of trade 2030 wrt. 2004	0.88	1.05	1.01	-	0.88	1.00	1.01	-
Policy		pol = +chi+dev+ind						
Welfare effect 2004-2030 wrt. bau	**0.22%**	**-1.09%**	**0.00%**	**-**				
CO$_2$ emissions 2004-2030 wrt. bau	**-30.74%**	**-16.12%**	**-10.58%**	**-40.34%**				
GDP 2030 (bill. 2004-US-$)	6843	14523	49180	70545				
CO$_2$ emissions 2030 (Gt)	2.79	11.08	12.07	25.94				
CO$_2$ sales 2030 (Gt)	1.75	1.40	-3.15	0				
CO$_2$ price 2030 (2004-US-$ per t)	-	-	-	56.03				
Energy productivity 2030 wrt. 2004	2.52	1.69	1.44	1.59				
Terms of trade 2030 wrt. 2004	0.90	0.96	1.04	-				

Table 2: Economic indicators of scenario *brown* (to be inserted in the main text)

Region	**CHI**	**DEV**	**IND**	**World**	**CHI**	**DEV**	**IND**	**World**
Policy		bau = -chi-dev-ind						
GDP 2030 (bill. 2004-US-$)	8726	15265	49197	73188				
CO_2 emissions 2030 (Gt)	14.07	16.84	16.49	47.40				
Energy productivity 2030 wrt. 2004	1.23	1.36	1.21	1.24				
Terms of trade 2030 wrt. 2004	0.76	1.21	0.98	-				
Policy		-chi-dev+ind				-chi-dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**0.31%**	**-0.36%**	**-0.22%**	**-**	**-1.56%**	**-1.06%**	**0.08%**	**-**
CO_2 emissions 2004-2030 wrt. bau	**5.82%**	**10.16%**	**-16.83%**	**-5.49%**	**3.97%**	**8.85%**	**-16.83%**	**-8.69%**
GDP 2030 (bill. 2004-US-$)	8693	14856	48911	72460	6806	12492	48856	68155
CO_2 emissions 2030 (Gt)	15.65	20.23	8.91	44.79	14.87	19.50	8.91	43.28
CO_2 price 2030 (2004-US-$ per t)	-	-	-	94.24	-	-	-	103.65
Energy productivity 2030 wrt. 2004	1.13	1.21	1.60	1.46	1.16	1.23	1.58	1.47
Terms of trade 2030 wrt. 2004	0.77	1.14	1.01	-	0.67	1.09	1.00	-
Policy		-chi+dev+ind				-chi+dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**0.73%**	**-1.22%**	**-0.06%**	**-**	**-1.47%**	**-1.08%**	**0.13%**	**-**
CO_2 emissions 2004-2030 wrt. bau	**11.41%**	**-17.54%**	**-11.61%**	**-17.99%**	**7.89%**	**-17.65%**	**-11.53%**	**-20.99%**
GDP 2030 (bill. 2004-US-$)	8800	14810	48986	72596	7085	14655	48969	70708
CO_2 emissions 2030 (Gt)	17.54	10.16	11.17	38.87	16.11	10.10	11.23	37.45
CO_2 sales 2030 (Gt)		2.27	-2.27	0		2.33	-2.33	0
CO_2 price 2030 (2004-US-$ per t)	-	-	-	68.69	-	-	-	72.62
Energy productivity 2030 wrt. 2004	1.03	1.73	1.38	1.41	1.09	1.73	1.37	1.41
Terms of trade 2030 wrt. 2004	0.77	1.09	1.02	-	0.65	1.06	1.02	-
Policy		+chi-dev+ind				+chi-dev+ind+bta		
Welfare effect 2004-2030 wrt. bau	**-1.27%**	**-0.53%**	**-0.16%**	**-**	**-0.91%**	**-1.49%**	**-0.02%**	**-**
CO_2 emissions 2004-2030 wrt. bau	**-33.96%**	**14.83%**	**-16.01%**	**-24.00%**	**-34.32%**	**12.85%**	**-15.79%**	**-26.01%**
GDP 2030 (bill. 2004-US-$)	8620	14672	48901	72193	8660	12706	48886	70253
CO_2 emissions 2030 (Gt)	4.55	22.07	9.40	36.02	4.47	21.11	9.49	35.07
CO_2 sales 2030 (Gt)	0.50		-0.50	0	0.59		-0.59	0
CO_2 price 2030 (2004-US-$ per t)	-	-	-	93.01	-	-	-	98.66
Energy productivity 2030 wrt. 2004	2.21	1.13	1.53	1.53	2.22	1.16	1.51	1.53
Terms of trade 2030 wrt. 2004	0.80	1.09	1.02	-	0.79	1.02	1.01	-
Policy		pol = +chi+dev+ind						
Welfare effect 2004-2030 wrt. bau	**-0.95%**	**-1.68%**	**0.04%**	**-**				
CO_2 emissions 2004-2030 wrt. bau	**-31.59%**	**-18.48%**	**-11.47%**	**-44.33%**				
GDP 2030 (bill. 2004-US-$)	8636	14395	48941	71972				
CO_2 emissions 2030 (Gt)	5.14	9.82	11.43	26.39				
CO_2 sales 2030 (Gt)	-0.09	2.61	-2.52	0				
CO_2 price 2030 (2004-US-$ per t)	-	-	-	88.71				
Energy productivity 2030 wrt. 2004	1.99	1.74	1.33	1.49				
Terms of trade 2030 wrt. 2004	0.82	0.97	1.04	-				

Table 3: Functions, sets and parameters

Symbol	Explanation
$f(.)$	General function
$ces(.)$ $[cet(.)]$	Constant elasticity of substitution [transformation] function
$cd(.)$	Cobb-Douglas function
$ltf(.)$	Leontief function
t	Time, year [2004; 2025] (climate policy starts in 2012)
r $[rr]$	Region {IND, DEV, CHI}
i $[ii]$	Sector, commodity (30 sectors, see footnote in section 3)
e	Fossil fuels {col, gas, oil} (subset of i)
ρ	Time discount rate (0.02 per year)
$\delta(r)$	Capital depreciation rate
$\sigma(r)$	Saving rate
$\lambda(t,r)$	Population growth rate plus rate of educational improvement
$\vartheta^A(r)$	Rate of exogenous general technological progress
$\vartheta^E(r)$	Rate of exogenous energy biased technological progress
$\tau^{(.)}(.)$	Tax rate
$\Upsilon(rr,r,i)$	Transportation costs (of transporting from rr to r)

Table 4: Variables

Symbol	Explanation
$W(r)$	Cumulated, discounted welfare effect
$U(t,r)$	Utility of the representative consumer
$P(.)$	Expenditure
$C(t,r)$	Consumption (private and public)
$D(t,r,i)$	Production for domestic use
$X(t,r,i) \quad [X(t,rr,r,i)]$	Exports [bilateral trade from rr to r]
$M(t,r,i)$	Imports
$K(t,r) \quad [\tilde{K}(t,r,i)]$	Capital endowment [production input]
$F(t,CHI) \quad [F(t,CHI,i)]$	Endowment of CHI with capital from IND [production input]
$L(t,r) \quad [L(t,r,i)]$	Labor endowment [production input]
$B(t,r) \quad [B(t,r,i)]$	Land and natural resources endowment [production input]
$EM(t,r,e) \quad [EM(t,r,e,i)]$	CO_2 Emissions permits endowment [production input]
$N(t,r,i) \quad [N(t,r,ii,i)]$	Intermediate good input [flow from ii to i]
$R(.)$	Total tax revenue
$p^{(.)}$	Price
$A(t,r,i)$	Total factor productivity
$E(t,r,i)$	Energy input
$FI(t,i)$	Foreign capital intensity in China $\left(\frac{F}{K}\right)$
$MI(t,i)$	Import intensity in China $\left(\frac{M}{D+X}\right)$
$NI(t,ii,i)$	Intermediate good flow intensity in China (from ii to i) $\left(\frac{N}{D+X}\right)$
$VI(t,i)$	Vertical linkage intensity in China with respect to upstream u and downstream d sectors $\left[\sum_{u\neq i} FI(t,r,u)NI(t,r,u,i) + \sum_{d\neq i} FI(t,r,d)NI(t,r,i,d)\right]$
$Y_L(t,r,i)$	Labor productivity $\left(\frac{D+X}{L}\right)$
$Y_E(t,r,i)$	Energy productivity $\left(\frac{D+X}{E}\right)$
$T^A(t,i)$	Rate of endog. general tech. progress in China
$T^E(t,i)$	Rate of endog. energy biased tech. progress in China