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Reconciling Climate Change and Trade Policy

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Abstract

There is growing clamor in industrial countries for additional border taxes on imports from countries with lower carbon prices. The authors confirm the findings of other research that unilateral emissions cuts by industrial countries will have minimal carbon leakage effects. However, output and exports of energy-intensive manufactures are projected to decline potentially creating pressure for trade action. A key factor affecting the impact of any border taxes is whether they are based on the carbon content of imports or the carbon content in domestic production. Their quantitative estimates suggest that the former action when applied to all merchandise imports would address competitiveness and environmental concerns in high income countries but with serious consequences for trading partners. For example, China's manufacturing exports would decline by one-fifth and those of all low and middle income countries by 8 per cent; the corresponding declines in real income would be 3.7 per cent and 2.4 per cent. Border tax adjustment based on the carbon content in domestic production, especially if applied to both imports and exports, would broadly address the competitiveness concerns of producers in high income countries and less seriously damage developing country trade.

This paper—a product of the Trade and Integration Team, Development Research Group—is part of a larger effort in the department to understand the policy implications of international economic integration. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at amattoo@worldbank.org.

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Reconciling Climate Change and Trade Policy

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I. Introduction

If countries cut emissions by different amounts, carbon prices are likely to differ across countries. Countries with higher carbon prices may seek to impose additional border taxes on imports from countries with lower carbon prices for two reasons. They may wish to offset the competitiveness disadvantage to their firms and the "leakage" of carbon emissions in the form of increased production in countries with lower carbon prices.

A key issue in the run-up to Copenhagen is therefore the scope for trade policy actions in any climate change agreement. The internationally-minded US Senator John Kerry and the free trade-oriented Senator Graham wrote recently in the New York Times that,

> *".. we cannot sacrifice another job to competitors overseas. China and India are among the many countries investing heavily in clean-energy technologies that will produce millions of jobs. There is no reason we should surrender our marketplace to countries that do not accept environmental standards. For this reason, we should consider a border tax on items produced in countries that avoid these standards. This is consistent with our obligations under the World Trade Organization and creates strong incentives for other countries to adopt tough environmental protections."*

Indeed, the eponymous legislation that these two senators are shepherding through Congress provides for such trade actions. President Nicholas Sarkozy of France joined the charge when he said, "We need to impose a carbon tax at [Europe's] borders. I will lead that battle." Nobel-prize winning trade economist, Paul Krugman issued his own endorsement, arguing that carbon taxes at the border are "a matter of leveling the playing field, not protectionism." And the WTO itself has given a cautious nod: "Rules permit, under certain conditions, the use of border tax adjustments on imported and exported products," says an appropriately guarded report, jointly issued by the trade body and the United Nations Environmental Program.

What is the likely impact of these measures? And how should they be optimally designed? These are the questions addressed in this paper.

Most of the existing literature focuses on the consequences for the industrial countries of unilateral emissions reductions and/or offsetting trade actions. The studies on the United States (Fischer and Fox, 2009; Ho et. al., 2008, Houser et. al., 2008) and the European Union (Aldy and Pizer, 2008; Grubb and Niehoff, 2006; Peterson and Schleich, 2007; Ponssard and Walker, 2008; Quirion and Demailly, 2006; Reinaud, 2005) typically examine two outcomes: the overall emissions reductions—the so-called leakage issue; and the impact on producers of energy-intensive goods in rich countries—the so-called competitiveness issue. The broad findings are that unilateral actions lead to relatively small leakage in terms of aggregate emissions. However, there can be larger emissions and competitiveness effects in some sectors, for example, cement, steel, and aluminum, which can be partially offset through trade actions. However, these papers do not quantify the impact of these trade actions on developing countries.

In contrast, Atkinson et. al. (2009) adopt a more global approach and calculate the effective tariff that exporting countries would face on their goods if all importing countries placed a small domestic emissions tax. However, even this study does not measure the resulting trade and output consequences. In general, few studies have adopted a global approach in trying to quantify simultaneously the effects on emissions, as well as sectoral exports and output of all countries, industrial and developing.

Hence, for many of the vital policy questions that are the subject of this paper, there are today no good answers based on empirical research. An econometric approach seems handicapped by the absence of past events, and our inability to construct experiments, which are comparable with the policy changes of greatest interest. We therefore use a multi-country, multi-sector CGE model to derive our quantitative estimates. In situations of simultaneous climate and trade policy changes of the kind that we consider in this paper, in which there could be significant interaction among the policies of different countries, and where we are interested in quantifying the effects of policy change on output and trade in different sectors of the economy, a computable general equilibrium (CGE) approach seems appropriate (Kehoe et. al., 2005).

The main empirical findings are the following. In a differentiated carbon price regime, there will be strong pressure in the industrial countries to take trade actions against countries that set low carbon prices. Environmental concerns cannot be the basis for such actions because "leakage"—increases in emissions in poor countries as a result of emission tightening in the rich—will be low. Given the stated level of ambition in the US and EU on unilateral emission reductions –17 per cent cuts relative to 2005 levels by 2020, the increase in emissions in low and middle income countries will be about 1 percent. Rather, the pressure will emanate from domestic producers of energy-intensive manufactures who will witness erosion in their competitiveness, reflected in export and output declines, which in the US could amount to 12 and 4 per cent, respectively.

A country which has imposed a tax on carbon emissions domestically (or equivalently introduced a domestic cap-and-trade scheme) can impose a tax on imports either based on the carbon content of domestic production or based on the carbon content embodied in imports.

Our estimates show that imposing tariffs across-the-board based on the carbon content of imports would address competitiveness concerns of domestic producers and contribute to further emissions reductions. But it would be a "nuclear option" in terms of trade consequences. For example, such an action by the US and EU would be the equivalent of imposing a tariff of over 20 percent on China and India, resulting in lost exports of up to 20 percent.

The second option of a trade action based on the carbon content in domestic production if applied symmetrically on exports and imports would allow energy-intensive producers in rich countries to regain most of the competitiveness that they stand to lose from emissions reductions action. The trade consequences of this option for developing countries would be less serious. The second option would, therefore, be the least harmful of possible border tax adjustments from a trade and developing country perspective though still inferior to no border tax adjustment.

This paper is organized as follows. In section II, we describe some recent initiatives on trade actions in the context of climate change legislation and the WTO status of such actions. In section III, we spell out the scenarios that underlie our empirical analysis. Section IV describes the simple analytics of emissions reductions, international tradability of emissions and transfers. In section V, we present the results of our quantitative analysis. In Section VI, we discuss the implications of our results for the optimal design of international rules on trade actions. Section VII provides a concluding assessment.

II. Recent Initiatives on Trade Actions and Their WTO status

The United States Congress has seen two recent legislative initiatives which create scope for some form of trade policy actions. The most recent, which is still being debated in the Senate (Boxer-Kerry), has a general provision that calls for border tax adjustments consistent with WTO provisions. This is not precise because the interpretation of existing WTO provisions is itself not settled. Greater specificity on border tax adjustments has been provided in a bill already passed by the House of Representatives (Waxman-Markey) which contains two kinds of provisions with potential trade impacts.

First, the bill contemplates the grant of free emission allowances to certain energy-intensive and/or trade-intensive industries (which are likely to include iron and steel, paper and paperboard, rubber manufacturing, plastics, organic and inorganic chemicals, and petrochemicals). The amount of allowances would depend roughly on the sector's output, its carbon intensity and the additional "tax" created by the emissions cuts. There are two ways of interpreting these allowances. If the allowances are related to historical output (it has been proposed that they be related to output in the previous two years), then they would amount to a lump-sum transfer without any marginal impact on production decisions, and hence on trade. Alternatively, producers' knowledge that future allowances are related to current output could have an impact on current decisions on output. In this case, allowances would be closer to a production subsidy. But it is important to note that in either case the magnitude of the allowance would be related to carbon intensity in *domestic* production.

Second, the bill would require importers in certain sectors (based on the same eligibility criteria as for emission allowances) to purchase emission allowances at the going market price. This measure would be equivalent to a border tax adjustment because it would serve to raise the price of imports.[1] But the magnitude of the border tax would depend on

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[1] Another form of "border tax adjustment" would be to enact an energy-performance or energy-intensity standard for certain products (say, a ton of steel cannot have a carbon-footprint of more than x tons of CO2) and impose that standard on both domestic steel and imported steel (Pauwelyn, 2009).

whether the purchase of allowances must cover the actual carbon content of imports or the carbon content in comparable domestic output.[2]

In the EU, no clear policy initiatives have so far been taken in relation to border tax adjustments. But the French President, Nicolas Sarkozy, has recently called for countries in the European Union to adopt carbon taxes and to impose adjustments at the border for these taxes. In his view, the idea was now "progressing" among EU leaders "because it is more and more understood, not as a protectionist measure," but as a way to "rebalance the conditions of free-trade and competition…Otherwise, it is a massive aid to relocations. We cannot tax European companies and exempt others."[3] Lord Turner, Chairman of the United Kingdom's Committee on Climate Change, while noting that the distribution of free carbon permits to affected companies had for the time being addressed competitiveness concerns, has stated that border tax adjustment might be a better solution in future. "Looking forward, we should keep an open mind about the two approaches."[4]

What about the WTO-consistency of these possible trade actions? WTO law and jurisprudence are evolving and not completely clear on what types of actions would be legitimate. The legality of both the free allowances and the border tax adjustments contemplated under the recent US bills is open (see Hufbauer et. al. 2009; Pauwelwyn, 2009, Bhagwati and Mavroidis, 2007, and WTO, 2009, among others for a thoughtful examination of the legal implications of possible trade actions).

If free emissions allowances are designed to simulate a pure transfer without any effect on marginal production decisions, they would probably not be inconsistent with the WTO. On the other hand, if they are designed to affect such marginal decisions, they could constitute a trade-distorting production subsidy. Unlike export subsidies, production subsidies per se are not prohibited by WTO rules (see Part II of the WTO Agreement on Subsides and Countervailing Measures (SCM) and Pauwelyn, 2009). Production subsidies are, however, actionable, including in the form of countervailing import duties by partner countries (See Part III of the WTO's SCM Agreement). However, legitimate action requires the fulfillment of a number of conditions, including demonstration of injury to a domestic industry (see part V of the WTO's SCM Agreement).

The WTO issue on border tax adjustments relates to the basic national treatment principle in Article III of GATT (1994). This Article clearly permits the imposition on imports of domestic indirect taxes provided the taxes on imports are no higher than the taxes levied

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[2] This requirement on importers would kick in for imports originating in countries that are not part of a future climate change agreement or that have not signed sector-specific agreements with the United States. The requirement would become effective from 2017 and seems to be the default option unless the President intervenes to waive it. The Waxman-Markey and Boxer-Kerry bills both call for this de facto border tax provision to take into account the free emission allowances that are granted under the provision described above. Presumably, this is to avoid producers in selected sectors from double-dipping—benefiting from the de facto subsidies under the free allowance provision *and* from the border tax adjustment on imports.

[3] See http://www.euractiv.com/en/climate-change/france-germany-call-eu-border-tax-co2/article-185580?Ref=RSS.

[4] See "EU attacks carbon border tax initiative," *Financial Times*, October 15, 2009.

on comparable domestic products. Under the WTO panel ruling in the Superfund case, indirect taxes levied on domestic inputs could also be imposed on imports provided these inputs were embodied in the final product (see WTO, 2009). However, there is no WTO jurisprudence on whether such adjustments are permissible for inputs (such as energy) that are used in production but are not themselves incorporated in the final product.[5]

It is less clear that even if such border tax adjustments were permitted at what level they could be set and whether they should be based on the carbon content of domestic production or foreign production. Even if there is a presumption in favor of the latter interpretation, there will be important practical considerations that might favor the former. Moreover, on scope, if border tax adjustments are permitted at all, there would be no constraints on the types of products on which they could be applied. Therefore in our empirical analysis below, we consider the effect of taxes which differ both in their basis (i.e. domestic or foreign carbon content) and in their scope (on imports of all products or on imports of only energy-intensive products).[6]

III. Scenarios

To compare the quantitative implications of recent initiatives, we constructed a set of scenarios (see Table 1). The benchmark scenario involves unilateral emissions reductions by high income countries, amounting to a 17 percent cut by 2020 relative to emissions levels in 2005. This scenario—NBTA17—is close to the unilateral cuts announced by the EU and the US (for example, the Boxer-Kerry bill calls for a 20 percent cut by 2020). We assume that low and middle income countries do not undertake any emissions reductions. Modeling cuts also by these countries is feasible but adds little to the analysis. While this 17 percent cut is the base case scenario, we examine the robustness of our results to a wide range of emissions cuts by the US and EU, ranging from 5 percent to 40 percent.

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[5] Rules on export subsidies do, however, state that rebates based on energy “consumed” in the process of producing goods for exports will not be deemed to be export subsidies (See Annex I of the WTO’s SCM Agreement). One argument could be that by symmetry comparable border tax adjustments should be permitted on the import side.

[6] There is a another option, which would be qualitatively different from those described above, in that it would punitively target all imports from countries with lower carbon prices and not necessarily be based on carbon content. The aim of such actions would be to attempt to change policies relating to carbon abatement across the board. These actions would be responding less to domestic trade concerns than to global environmental concerns. But this option would only be legitimate if it could be justified under the WTO’s exceptions provisions in XX (b) or XX(g) relating respectively to measures necessary to protect human, animal or plant life or health and measures relating to the conservation of exhaustible natural resources. Here we are very much in the murky waters of the WTO shrimp turtle case (see Pauwelyn, 2009). What WTO jurisprudence, notably in this case, has established is the permissibility of national trade policy action to protect the global environment (i.e., to address cross-border externalities). However, this right comes attached with a number of conditions that must be met, including the requirement that such action be “necessary,” to achieve the objective. Recent interpretations of the necessity test have required the exhaustion of other reasonable means—notably international cooperation--of attaining the environmental objective.

To depict the alternatives being considered in EU and US legislation, we model three broad policy options. The first option is a border tax adjustment based on the carbon content embodied in the domestically produced good in the importing country; we call this BTADU.[7] Thus, if the US has a CO_2 tax of say $60 per ton, and the direct and indirect CO_2 content in car production in the United States is 10 tons, the US could apply a CO_2 tax of $600 on the imports of cars.

The second option is a similar tax adjustment except that it is based on the carbon content embodied in imports, BTAFU. In the same example, if the direct and indirect CO_2 content in Indian car production is 20 tons, the US could apply a CO_2 tax of $1200 on the imports of cars from India.[8]

A third option would be to combine a border tax adjustment on imports with a similar border tax adjustment on exports thus relieving exporters also of the burden of taxes on carbon, which we call scenario BTADE. Since export rebates would have to be based on the carbon content in domestic production, consistency would require that in this scenario, the tax adjustment on imports is also based on the carbon content in domestic production.

The BTADU scenario can be seen as representing an upper bound on the trade impacts of the US (and EU) free emission allowances program. As discussed earlier, this program could either have no effects on output and trade or act like a production subsidy. The BTADU scenario involves a tax on imports, which is the sum of a production subsidy and consumption tax, and will overstate the effect of the allowance program. What makes BTADU comparable with the production subsidy variant of the free allowance program is that the basis for the assistance is the carbon intensity in domestic production.

The BTAFU scenario can be seen as reflecting border tax adjustment under the provision in draft US legislation requiring importers to buy emission allowances equal to the carbon content of imports, as well as under the proposals of the French president. Analytically, this is a border tax based on how much production costs in the source (developing) country would have increased if it had imposed an identical carbon tax.

The US and EU legislative initiatives do not explicitly provide for the BTADE option, involving export rebates of carbon taxes. This probably reflects the concerns of environmentalists: it would be odd to be taking action on environmental grounds and yet exempt some part of domestic production (namely, exports) from carbon taxes. But it is important to consider this policy option. The options in BTADU and BTAFU are theoretically problematic because they do not create neutral incentives between imports and exports and involve a tax on trade. As Grossman (1982) argued, neutrality in indirect taxes such as the VAT could be achieved only if border tax adjustments are symmetric between imports and exports.

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[7] Note that in all the border tax scenarios, we assume that the adjustment is based on the total carbon content (i.e. direct and indirect), data on which are shown in Table 4.

[8] As is evident from this example, border tax adjustments based on carbon content in imports could vary based on the source of imports.

While these are the four main scenarios we will examine in detail, we need to deal with another set of possibilities. As currently drafted, US legislation envisages relief mainly for producers in energy-intensive sectors, which include chemicals, paper, ferrous metals, non-ferrous metals, and mineral products. But in the four main scenarios, we assume that border tax adjustments are applied on *all* merchandise imports. We do so to highlight the analytics of the various policy options and also because the application of border taxes across-the-board cannot be ruled out either in the US or EU. However, we will also discuss briefly the consequences of restricting these adjustments only to imports of energy-intensive goods (scenarios BTADR and BTAFR).

IV. The Simple analytics of unilateral emissions reduction and trade policy actions

We can think of emissions (*E*) as an input to the production of a single composite commodity with a simple production function which is assumed to be given over the relatively short horizon that we consider in this paper.[9]

We depict the equilibrium for the world in Figure 1. V and V^* represent the value of marginal products of emissions (i.e., the price of the output times the marginal physical product of emissions) for the two groups of countries, say the poor and rich, respectively. Emissions are measured from the origin O for the poor country and O* for the rich countries. In the pre-emissions situation, we assume that the price of emissions is zero in both groups of countries. In each group the equilibrium is where the marginal benefit of emissions equals the zero price of emissions. This occurs at E, resulting in an initial level of world emissions of OO^*, with OE the emissions level of the poor and O*E, the emissions level of the rich.

We assume that only rich countries take actions to reduce emissions. Thus, the origin for measuring their emissions shifts inward from O^* to O_1^* and the value of marginal product to V_1^*. The price of emissions rises to P_1^* in the rich countries and remains at zero in the poor countries. In this case, rich country output declines and rich country firms become less competitive because of their increased costs. This can be depicted as a rightward shift in the value of marginal product curve for poor countries to V_1 because they would now receive a higher price for their output. We can therefore think of the output declines of the rich countries and the expansion of output in the poor countries as together constituting the competitiveness consequences of unilateral emissions reductions action by rich countries.

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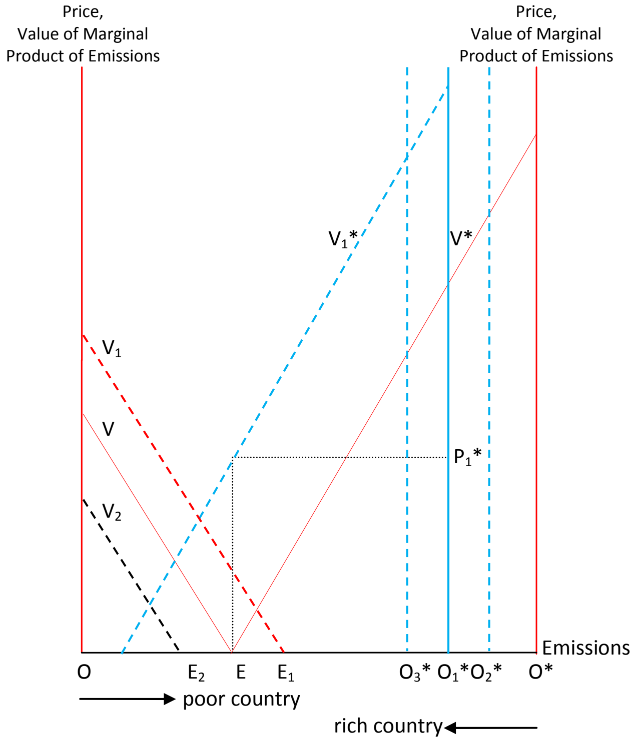
[9] See e.g. Panagariya (2009).

Figure 1: Unilateral Emission Reduction and Trade Policy Action



In order to illustrate the impact on global emissions, we depict this rightward shift of the V curve and the corresponding increase in poor country emissions by moving the origin for the rich countries to O_2^*. Note that this shift represents the leakage effect: while rich countries reduce their emissions by $O^*O_1^*$, some of it is offset as poor countries increase their emissions by EE_1 ($=O_1^*O_2^*$), and so the global reduction in emissions is only $O^*O_2^*$.

What about the impact of trade action by rich countries on emissions and output in the poor countries? Essentially, if rich countries impose a tariff on exports from poor countries, the effect is akin to depressing the price they receive for their output. In the figure this can be shown as a leftward shift from V_1 to V_2 of the value of marginal product curve for poor countries. However, in order to capture the emissions impact of this, we show this as a leftward shift of the origin for rich countries from O_2^* to O_3^*. So with trade action, as rich countries reduce their emissions by $O^*O_1^*$, poor countries also reduce their emissions by EE_2 ($=O_1^*O_3^*$), so the global reduction in emissions is greater at $O^*O_3^*$. Clearly, the magnitude of these shifts will depend on the severity of trade restrictions to which we turn next.

V. Quantification of the impact of unilateral emissions reduction and trade policy actions

For many of the vital policy questions that are the subject of this paper, there are today no good answers based on empirical research. An econometric approach seems handicapped by the absence of past events and our inability to construct experiments which are comparable with the policy changes of greatest interest. In situations of simultaneous policy changes of the kind that we consider in this paper, in which there could be significant interaction effects among different countries, and where we are interested in quantifying the effects of these changes on output and trade in different sectors of the economy, a computable general equilibrium (CGE) approach seems appropriate (Kehoe et. al., 2005).

The quantitative results presented in this paper rely on a specific CGE model that has been developed at the World Bank, known as the Environmental Impact and Sustainability Applied General Equilibrium Model, or the ENVISAGE model.[10] The primary purpose of the ENVISAGE model is to assess the growth and structural impacts for developing countries from climate change itself and policies to address climate change—either unilaterally or in an international agreement.

Any quantitative analysis in this field will conditional on assumptions regarding exogenous developments (for example the future cost of alternative technologies), key parameter values (for example intra-fuel substitution elasticities) and model specification (for example carbon tax revenue recycling). Our quantitative exercise is meant to be illustrative of the signs and broad magnitudes of effects, rather than be taken as definitive in any way. The reader should nonetheless keep in mind certain caveats regarding the model and its results.

First, and foremost, the model is not equipped to quantify any of the welfare benefits from emissions reductions per se and does not take account of emissions related to forestry.

Second, the modeling does not take into account any pre-existing subsidies or other distortions in developing country energy markets whose elimination could provide opportunities for emission abatement. The OECD (2009) has calculated the fuel subsidies in a number of developing economies. Most of these are consumption rather than production subsidies and, although they vary across fuel types and income groups, their average value is relatively low (for example, less than 3 percent for China). This suggests that eliminating these subsidies will have positive welfare consequences that our results do not incorporate. However, the fact that the magnitudes are low would suggest that our results relating to compositional changes may not be significantly affected.

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[10] The model has several distinguishing features: a focus on developing countries and significant sectoral disaggregation; an integrated climate module that generates changes in global mean temperature based on emissions of four greenhouse gases; and economic damage functions linked to changes in temperature. A summary description of the model and the key assumptions are provided in the Technical Appendix and van der Mensbrugghe (2009) provides a full description of the model.

Third, the model is not able to represent the full range of available alternative technologies, and so may tend to exaggerate the output and trade responses as energy prices rise with emission limits. But some features of the model may limit the biases on this score. We allow for exogenous improvements in manufacturing energy efficiency through the accumulation of more advanced capital stock. Also, the current version of the ENVISAGE model does allow for limited substitution between technologies. For example, it allows for switching to alternative (and cleaner) technologies in the power sector, albeit in limited fashion.[11] The model also allows for some substitution to natural gas in the transportation sector but not to biofuels and only to a limited extent to electricity (to the extent some modes of public transportation already rely on electricity).

The limited possibilities for technological substitution may not be unrealistic given that our horizon is relatively short-term: we are projecting economic magnitudes for 2020, about ten years out from today. Also, the emission taxes and the consequential price changes in our model are relatively small. For example, in the most extreme scenario, when both high and low income countries reduce emissions, the overall price of energy rises by 41 percent in China and 26 percent in India. These prices are not large enough to induce large technology switching responses. For example, Birdsall and Subramanian (2009) find that it took the oil price shock of the 1970s—which involved a quadrupling of energy prices—to induce a small response in energy efficiency in production and even more modest response on the consumption side.

We describe first the benchmark scenario where high income countries make unilateral emission reductions and then turn to the implications of trade policy action.

No trade policy actions

In the benchmark scenario, which we call the NBTA (no border tax adjustment), we assume that after 2012, a carbon tax is imposed in OECD countries to achieve a 17% cut of total OECD carbon emission by 2020 (relative to the 2005 level).

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[11] The current electricity technologies include five activities—coal, oil and gas, hydro, nuclear and other (essentially renewable). The five activities are aggregated together to ‘generate’ a single electricity commodity distributed to households and producers. The ‘aggregator’ (for example the electricity distribution sector) chooses the least cost supplier subject to a CES aggregation function (that is calibrated to base year shares). Thus the coal producer will see a decline in demand relative to other producers—particularly hydro, nuclear and other—when subject to the carbon tax. The amount of the shift will depend on both the overall demand elasticity as well as the base year share. In the current baseline, these shares are fixed at base year levels. It is clear that there are non-price factors that are pushing these shares in one direction or another and we are witnessing rapid rises (from a very low base) in renewable technologies (notably wind and solar). In the model, and in reality, expansion of hydro is limited to physical potential. We make no effort to model changes in the share of nuclear power. In addition, the model ignores one potentially significant change in power generation and that is the introduction of carbon capture and storage (CCS) for coal and gas powered thermal plants. However, CCS is unlikely to become a major technology before 2020 (though its anticipation could affect investment decisions in the near term). CCS may also be a feasible technology in some other fossil-fuel dependent sectors such as cement and iron and steel production.

We first focus on the competitiveness effects in industrial countries. The quantitative impacts are summarized in Table 2.[12] The imposition of a carbon tax by OECD countries can be expected to curtail domestic output of all carbon-intensive goods and services, ranging from coal, oil and natural gas to electricity, but competitiveness effects will be felt most sharply in the case of tradable goods like chemicals and plastics, paper products, minerals like cement, ferrous and non-ferrous metals. Table 2 confirms that the impact of unilateral emissions reductions by the rich countries will lead to an increase in imports and decline in the exports and output of the US and EU. For example, exports of energy-intensive manufacturing goods decline by 12 percent in the US and 5 percent in the EU, whereas output of these goods declines by 4 percent in the US and by 2 per cent in the EU. The effects are greater in the US than the EU because both energy and carbon intensity of these sectors in the US is nearly double that in the EU (Table 4). This also helps understand why calls for trade action at the border are more insistent in the US than the EU.

Since developing countries do not impose comparable taxes, the action by the high income countries leads to increased imports of carbon intensive products from countries like Brazil, China and India, which therefore see an expansion in exports of these products of about 6-8 per cent. However, what matters for emissions is the impact on these countries' overall output and its composition. Since exports are a small proportion of output, the increase in output of carbon intensive sectors in Brazil, China and India, is only about 1-2 per cent (Appendix Table 5). Furthermore, this expansion pulls resources out of other sectors, which has an offsetting effect on emissions even though these latter sectors are less carbon intensive. As a result, the "leakage" effect is quite small–the emissions in low and middle income countries are only 1 per cent higher than business-as-usual levels (Table 3). For example, China's emissions increase from 3679 to 3700MtC and India's from 805 to 811 MtC. Thus, given the assumptions of our model, the limited unilateral action envisaged by high income countries to reduce their carbon emissions will not in and of itself lead to a large increase in emissions in poor countries.[13]

Impact of trade policy actions based on carbon content in domestic production

Despite the limited leakage effect, there is likely to be pressure on industrial countries – e.g. from their own-energy intensive industries which will face serious competitive pressures, as our estimates indicate--to take trade policy actions, most likely in the form of additional border taxes on imports from countries that do not tax emissions at comparable levels.

BTADU involves a border tax applied on all imported products equivalent to that imposed on the carbon content in the like domestic product. The effects of such a tax on

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[12] In the text, we focus on the impact on selected countries—US, EU, China, India, and Brazil—and selected groups—high income and low and middle income. More disaggregated impacts and other data are presented in Appendix Tables 2-8.

[13] Of course, this result, like all others, is conditional on the supply/demand elasticities of our GE model. For a comparison of our results with those of other models, see the section on "Unilateral Action and Leakage" in the Technical Appendix.

output and exports in the industrial countries imposing this tariff are summarized in Table 2. The average tax across all goods is about 3-5 per cent, but the level is a little higher on energy-intensive goods 6-8 (Table 5). This import tax dampens the adverse output and trade consequences of the carbon tax increase for industrial countries. For example, imports of energy-intensive goods now decline by 4.6 percent (compared to a 3.5 percent increase without import action) in the US and output of such goods declines by 3.6 percent compared with a 4.4 percent decline without offsetting trade action (Table 2).

The impact on developing countries in the BTADU scenario is summarized in Table 6. Changes in welfare and output of low and middle income countries are less than one percent and exports decline by around 3 percent.

Impact of trade policy actions based on carbon content in imports

More disruptive trade action would involve border tax adjustments based on the carbon content in imports and applied to all manufacturing sectors (BTAFU). Note first that such an action would address both competitiveness and environmental concerns in industrial countries. Manufacturing output in energy-intensive industries in the US would now decline only by 2.5 percent and in the EU it would actually increase by 1.8 percent. These effects are not now concentrated only in energy intensive manufacturing but spread out over the entire manufacturing sector. As a result, the effects on aggregate manufacturing in high income countries are positive, resulting in an increase in output. Under this scenario, low and middle income countries' emissions would also decline by 1.5 percent as against the zero impact when actions are based on the carbon content of domestic production.

These outcomes in the high income countries would come at a huge cost for developing country trading partners. Since production in countries like China and India is much more carbon-intensive than in OECD countries, import taxes on all manufactured goods in the BTAFU scenario are much higher than in the BTADU scenario – an average tariff on manufactured goods imports from China of about 26 percent and from India of about 20 per cent (Table 5).[14]

As a result, for China, *aggregate* manufacturing exports decline by about 21 per cent, and for India, by 16 per cent, and manufacturing output by close to 3.5 percent in both countries (Table 6). Brazil is much less affected because its exports are far less carbon-intensive.

The impact in welfare is also significant. Whereas the BTADU scenario would have smaller effects on welfare in China, India and all low and middle income countries, the BTAFU scenario would reduce welfare in these countries by, respectively, 3.7, 1.4 and 2.4 per cent (Table 6).

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[14] Production could be relatively carbon intensive in developing countries for these broad GTAP categories both because individual products are produced more carbon-intensively and because the broad product categories include more carbon-intensive products.

Thus, trade policy actions based on the carbon content of imports applied to all imports would have substantial effects.

Impact of trade policy actions based on carbon content in domestic production but applied to imports and exports

Recall that border tax adjustments in the BTADU scenarios are akin to a tariff on imports. Trade theory suggests that a tax on imports is also a tax on exports and so this type of adjustment taxes trade twice, and is likely to be inefficient. From Grossman (1982) and Lockwood and Whalley (2008), we know that the way to eliminate the distortion would be to have symmetric tax adjustments so that the indirect tax burden on exports is also relieved. We call this the efficient border tax (BTADE).

Efficient border taxes (BTADE) will allay the competitiveness concerns in industrial countries to a greater degree than the corresponding tax adjustment applied only to imports (BTADU). This is not surprising because in these countries, exporters' competitiveness is also improved. Thus, energy-intensive manufacturing sectors in the US witness a decline in output of 0.8 percent under BTADE compared with 1.2 percent in BTADU. In the EU, BTADE actually allows a more than full claw-back of competitiveness losses for energy-intensive producers because output increases by 1 percent compared with a 0.2 percent decline in the BTADU scenario.[15]

The impact on developing county trade is also unambiguously smaller under BTADE (and of course much smaller than under the BTAFU scenario) than under BTADU. For example, manufacturing exports of China and India decline by 1.8 percent and 2.1 percent respectively in the BTADE scenario compared with 3.4 and 3.2 percent, respectively in the BTADU scenario. This seems to be in accordance with the Grossman result (1982) that the BTADU border adjustment taxes trade and hence shrinks trading opportunities also for partner countries.[16]

A symmetric border tax adjustment would also be superior to the alternatives (BTAFU and BTADU) from a global efficiency perspective. We know that trade actions based on carbon content in imports imply a very high tariff and hence lead to large global efficiency losses of 1 percent. Under BTADE and BTADU, welfare declines are nearly halved, with BTADE being superior to BTADU. Global welfare declines by 0.52 percent in the former and by 0.58 percent in the latter. Global emissions also decline marginally more in the BTADE scenario (10 percent) than in the BTADU scenario (9.8 percent).[17]

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[15] In fact, efficient border tax adjustment (BTADE) addresses the competitiveness concerns of the energy-intensive sectors in some high income countries such as the US even more effectively than the drastic action in the BTAFU scenario. The reason is that the output benefits of export rebates are greater than of further increases in tariffs.

[16] However, the BTADE scenario is not superior to the BTADU scenario for developing countries' manufacturing output.

[17] Another way of understanding the BTADE scenario is as a consumption tax on emissions, and the no border tax adjustment scenario (NBTA17) as a pure production tax on emissions. Global welfare decline is marginally lower in the NBTA scenario compared with BTADE scenario (0.49 percent versus 0.52 percent)

The foregoing discussion suggests that from the perspectives of political economy in industrial countries, trade interests of developing countries and of global efficiency, symmetric and efficient border tax adjustment (BTADE) is the least undesirable alternative.

Impact of trade policy actions based on their product coverage

Thus far, we have examined the impacts of trade actions applied to all merchandise imports. What if they are only applied to energy-intensive imports? It turns out that if border taxes were applied only to energy-intensive imports, they would broadly achieve the goals of minimizing the adverse competitiveness effects in industrial countries from unilateral emissions reductions while also moderating the trade impact on developing country partners. For example, the decline in output of energy-intensive manufacturing output in the US in the BTADR and BTAFR scenarios are respectively 2.6 and 0.5 percent. The decline in China and India's manufacturing exports are between 1-3 percent in both scenarios.

Despite these results, limiting the scope of trade actions to energy-intensive products would have problems that we discuss below.

Robustness to different emissions reductions by high income countries

Are our results contingent on the specific assumption we have made about emissions reductions by industrial countries? We replicate the analysis above for a range of assumptions about unilateral emissions reductions by high income countries, ranging from 5 percent to 40 percent, complemented with offsetting trade actions. The results are depicted in Figures 2 and 3.[18] Figure 2a captures the effects on global emissions. It shows that the magnitude of global emissions decline is related to the size of the cuts by industrial countries. Also, the largest emissions declines occur when border tax adjustments are taken on all products based on the carbon content in imports (BTAFU). But the difference in emissions reductions is not significant across scenarios. The reasons are suggested in Figure 2b, which depicts the possible leakage of emissions to developing countries. The greatest leakage occurs, unsurprisingly, in the case of unilateral emissions reductions without offsetting trade action. But even in this case, the leakage is small—a maximum of 2.5 percent increase in emissions when industrial countries reduce emissions by 40 percent. The reasons for this, as explained above are two-fold: emissions reductions by high income countries increase developing countries' exports of energy-intensive goods, but exports are a small fraction of output, moderating the emissions impact. Moreover, in the long run and under full employment, any expansion of energy-

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but the emissions decline is greater in the BTADE scenario than in the BTADU scenario (10 percent versus 9.3 percent). Thus, a pure consumption-based tax is overwhelmingly superior to a tax that distorts trade (BTADU) but not unambiguously superior to a pure production tax.

[18] For presentational clarity, we focus on the four main scenarios: NBTA17, BTADU, BTAFU, and BTADE.

intensive sectors will lead to a contraction of other sectors, further moderating the emissions impact.

Figure 2a: Impact of Unilateral Emissions Reductions by Industrial Countries on Global Emissions (% change: relative to BAU in 2020)

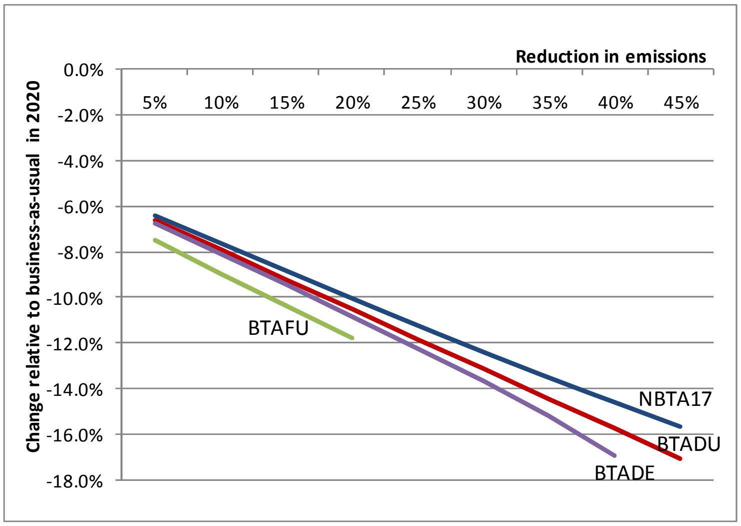


Figure 2b: Impact of Unilateral Emissions Reductions by Industrial Countries on Emissions of Low and Middle Income Countries(% change: relative to BAU in 2020)

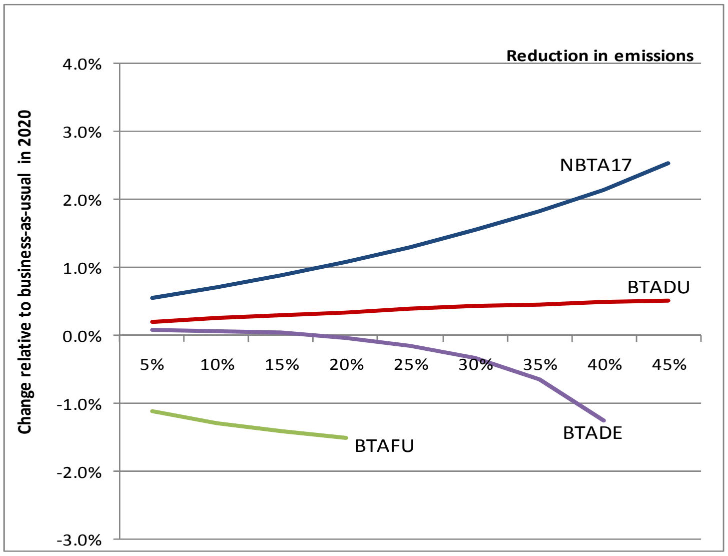


Figure 3a illustrates the competitiveness impact in industrial countries. The larger the emissions reductions the greater the negative impact on competitiveness (all the curves – except in the scenario BTADE - are downward sloping and the scenario with no offsetting trade action is the most steep). The milder form of trade action (BTADU) can claw back most of the competitiveness effects (the curve associated with this scenario are closer to the x-axis). The extreme form of trade action (BTAFU) is even more successful in clawing back the competitiveness loss from unilateral emissions reduction. But it is the efficient border tax adjustment (BTADE) that is successful in more-than-offsetting the impact of unilateral emissions reductions. The main reason is that the BTADE regime addresses the competitiveness loss not just in the domestic market but also in foreign markets.[19]

Figure 3a: Impact of Unilateral Emissions Reductions by Industrial Countries on their Output of Energy-Intensive Manufacturing (% change: relative to 2005 for emissions reductions; and relative to BAU in 2020 for output)

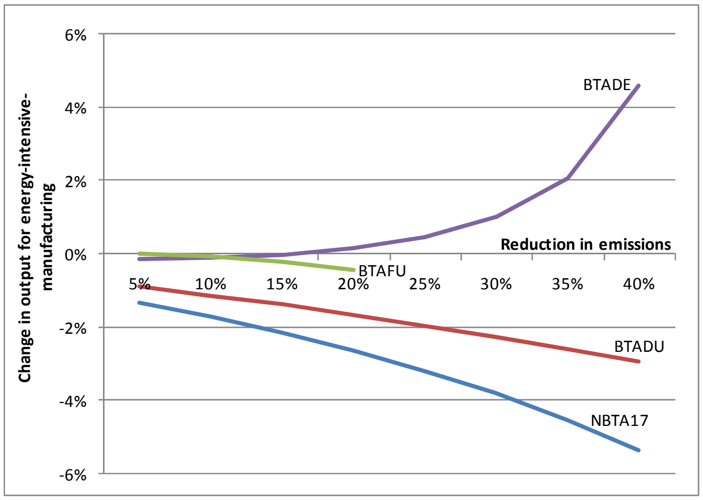
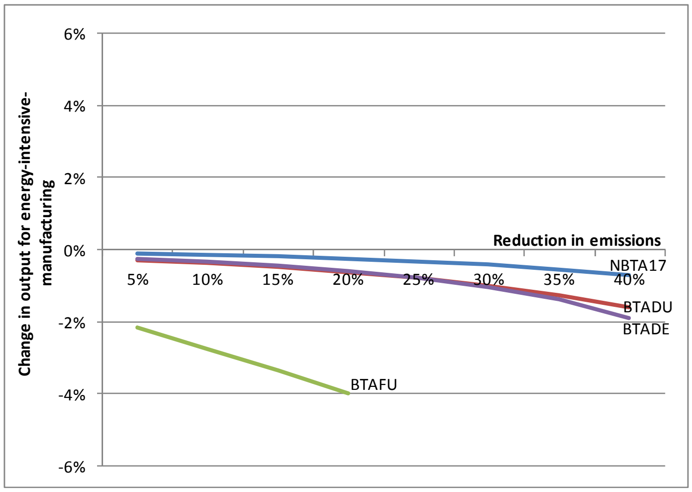


Figure 3b: Impact of Unilateral Emissions Reductions by Industrial Countries on China's Manufacturing Output (% change: relative to 2005 for emissions reductions; and relative to BAU in 2020 for output)



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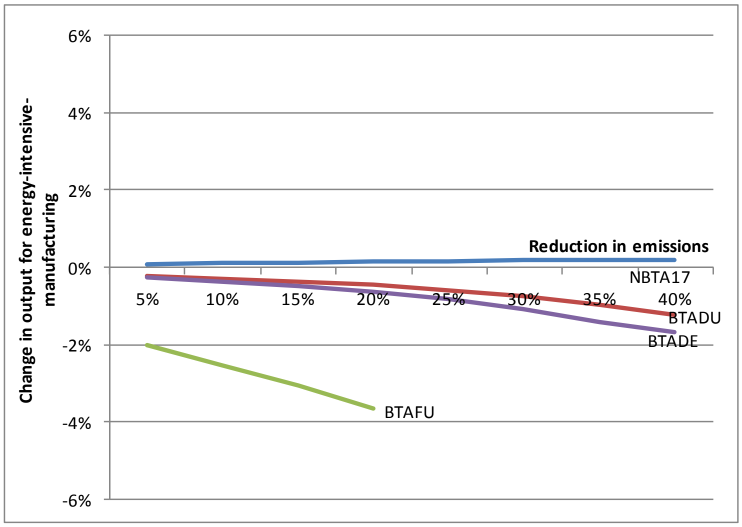
[19] The BTADE results are sensitive to the manner in which subsidies are calculated. In the analysis presented in the text, subsides are linked to ex ante (base-year) levels of carbon content as is likely to be done in practice. But insofar as exporters reduce the carbon content of their production in response to higher energy prices, they are in effect over-compensated and the higher output is the consequence. We also re-did the scenarios with border taxes based on the ex post carbon content (results are available from the authors upon request).

Figure 3c: Impact of Unilateral Emissions Reductions by Industrial Countries on India's Manufacturing Ouptut (% change: relative to 2005 for emissions reductions; and relative to BAU in 2020 for output)



The impact on China and India is shown in Figures 3b and 3c. The impact on manufacturing output remains relatively muted when no trade policy actions are taken (NBTA17) or when the trade policy action is based on domestic carbon content (BTADU and BTADE). But actions based on the carbon content of imports and applied to all merchandise imports lead to a dramatic decline in exports, with the magnitude depending on the extent of unilateral emissions reduction by industrial countries (BTAFU).

VI. Implications for International Trade Rules

From a purely trade perspective, the best outcome would be to have no scope for carbon-based border tax adjustment. However, as we have noted in the introduction, unconstrained border tax adjustments are already under consideration and enjoy a certain measure of support, including from the WTO. It may, therefore, be useful to identify the least undesirable alternative which our results suggest is border tax adjustments based on the carbon content of domestic production and applied symmetrically to imports and exports.

How would the different alternatives relate to existing trade rules? Recall that current WTO rules and jurisprudence are not settled. If indirect taxes on inputs such as carbon/energy that are consumed in production can be subject to border tax adjustment, then it would seem that taxes based on both domestic and foreign carbon content would be permissible. If, on the other hand, taxes on consumed inputs cannot be subject to border tax adjustment, then it would seem that neither basis for border adjustments would be permissible. Of course, both bases for applying border taxes could be justified by the environmental exceptions provisions of Article XX (GATT, 1994), but that avenue itself is untested and uncertain.

What if WTO members, in order to resolve this uncertainty and to preclude unilateral action, incorporated a principle that allowed symmetric border tax adjustment based on carbon content in domestic production? Presumably, they could invoke existing law which already allows such border tax adjustments in the export subsidy rules.

This option would be different from the proposal made in Hufbauer et. al (2009) who suggest a hybrid of the origin and destination-based rule for border tax adjustments. In their scheme, a country would not rebate exporters the emissions taxes applied to domestic production, reflecting the origin principle. Hufbauer et. al (2009), however, would allow a country to apply a border tax adjustment on imports if the domestic emissions tax in the importing country is greater than in the exporting country, reflecting the destination principle. As noted above, this amounts to double taxation of trade. They also do not specify whether the border tax adjustment on imports would be based on the carbon content of imports or domestic production. Thus, their proposal could correspond to our scenarios BTADU or BTAFU. And as we have shown, these scenarios are dominated by the symmetric border tax adjustment applied to imports and exports and based on the carbon content in domestic production (the BTADE scenario).

It is important to note that the symmetric border tax adjustment option is vulnerable to the slippery slope argument. If the principle is accepted that border tax adjustments could be applied to non-embodied inputs consumed in the process of production, then this might open the door to similar adjustments for taxes on other inputs that are not embodied, and perhaps to other domestic taxes and regulations more broadly. This is another argument for not allowing the principle of carbon-based border tax adjustment in the first place.

What about the alternative of limiting the scope for trade actions to energy-intensive imports, which our results suggest would be close to the symmetric border tax adjustment from a trade perspective? There are a number of problems with this approach, though.

First, it would still leave room for border taxes based on the carbon content of imports. But taxes based on domestic carbon content are preferable to those based on the carbon content of imports. The former, by virtue of being uniform across sources of imports, will require less information (the carbon content in the domestic economy rather than that in all importing countries) and therefore be easier to implement and less open to abuse. Administrative efficiency and political economy would thus argue in favor of border taxes limited to those based on the carbon content of domestic production. But even taxes based on the carbon content in domestic production would not be easy to implement: a range of issues, including the level of industry disaggregation for calculating carbon content, would need to be addressed (see WTO, 2009).

Second, even if trade actions were initially restricted to energy-intensive goods, they could provoke demands for extension: non-energy-intensive sectors would ask why they were being excluded from import relief, especially given, as our data shows, that there are large cross-country differences in total carbon intensity even in non-energy-intensive sectors (see Table 4). The risk that rules to restrict trade action to selected sectors could be vulnerable in this manner (i.e., open to future extension) is suggested by a recent EU Council decision on border tax adjustments.[20]

Third, a rule that would allow trade actions to be based on the carbon content of imports could not be symmetrically applied to exports. Recall that border tax adjustments that preserve neutrality of incentives should strictly speaking apply to imports and exports. Such symmetric adjustments do not seem to be under consideration currently but they could be in future. Symmetric border tax adjustment would have to be applied on the same basis and that basis would have to be the carbon content of domestic production.

VII. Conclusions

Under the range of likely emissions reductions being envisaged by the major industrial countries, there will be clamor to offset the competitiveness pressure of imports from countries which make less ambitious reductions. For example, if industrial countries reduce emissions by 17 percent by 2020 relative to 2005 levels, energy-intensive industries in the US will face output declines of around 4 percent. There will also be demands from environmentalists for trade action on the grounds of emissions "leakage" but our estimates show that these concerns are not warranted.

Analytically, industrial countries can respond to competitiveness concerns by imposing tariffs or border tax adjustments. The most extreme form of trade action would be one that is based on the carbon content of imports and applied to all merchandise imports. This would no doubt address the competitiveness and environmental concerns in high income countries but would come at the price of seriously damaging the trade prospects of developing country trading partners. Such an action would imply average tariffs on merchandise imports from India and China of over 20 percent and would depress manufacturing exports between 16 and 21 percent.

A border tax adjustment that is applied to imports and exports and based on the carbon content in domestic production would broadly address the competitiveness concerns of producers in high income countries while inflicting less damage on developing country trade. This option is, therefore, the least undesirable from a developing country trade perspective. Therefore, as part of any international agreement on climate change, all countries could seek to negotiate rules in the WTO that would either prohibit all forms of carbon-based border tax adjustment, or at most allow under the strictest conditions the least undesirable option.

We would stress the desirability of international agreement on trade actions being pursued as part of an international agreement on climate change rather than left to future negotiations in the WTO. Otherwise developing countries will remain vulnerable to trade policy action, especially in its extreme version. Not only would such a state of affairs render uncertain the overall benefits for developing countries of international cooperation on climate change, it might actually vitiate the atmosphere and hence worsen the prospects for achieving such cooperation.

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[20] http://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/110889.pdf

References

Aldy, Joseph E. and William A. Pizer, (forthcoming), “The US Competitiveness Impacts of Domestic Greenhouse Gas Mitigation Policies: Report for the Pew Center on Global Climate Change.

Armington, Paul, (1969), “A Theory of Demand for Products Distinguished by Place of Production,” *IMF Staff Papers*, Vol. 16, pp. 159-178.

Atkinson, Giles, Kirk Hamilton, Giovanni Ruta and Dominique van der Mensbrugghe (2009), “Trade in ‘Virtual Carbon’: Empirical Results and Implications for Policy,” Background paper for World Development Report 2010, The World Bank, Washington, DC.

Babiker, Mustafa (2005), “Climate change policy, market structure, and carbon leakage,” *Journal of International Economics*, 65, pp. 421-445.

Bhagwati, Jagdish and Petros C. Mavroidis, (2007), “Is Action Against US Exports for Failure to Sign the Kyoto Protocol WTO-legal?” *World Trade Review* 6: 299-310

Birdsall, Nancy and Arvind Subramanian (2009),”Energy, not Emissions: Equitable Burden-Sharing on Climate Change,” mimeo. Washington D.C.

Burniaux, Jean-Marc and Joaquim Oliveira Martins, (2000), “Carbon Emission Leakages: A General Equilibrium View,” Economics Department Working Papers, No. 242, May, OECD, Paris, France.

Burniaux, Jean-Marc, Giuseppe Nicoletti and Joaquim Oliveira-Martins (1992), “GREEN: A Global Model for Quantifying the Costs of Policies to Curb CO_2 Emissions,” OECD Economic Studies, No. 19, Winter 1992, pp. 49-92, OECD, Paris.

Cline, William R. (2007), “Global Warming and Agriculture: Impact Estimates by Country,” Center for Global Development and Peterson Institute for International Economics, Washington, DC.

Fisher, Carolyn, and Alan K. Fox (2009), “Comparing Policies to Combat Emissions Leakage,” Resources for the Future Discussion Paper 09-02, February.

Friedman, Thomas (2009), New York Times. September 27. Available at http://www.nytimes.com (Accessed on October 5, 2009).

Grossman, Gene, 1982, “Border Tax Adjustment,” *Journal of International Economics*, vol. 10, no. 1, February 1980.

Grubb and Niehoff (2006), “Allocation and Competitiveness in the EU Emissions Trading Scheme: Policy Overview. Climate Policy 6(1):137-160.

Ho, Mun, Richard D. Morgenstern, Jhih-Shyang Shih (2008), “Impact of Carbon Price Polciies on US Industry. RFF Discussion Paper 08-37. Washington DC: Resources for the Future.

IPCC (2000), *Special Report on Emissions Scenarios*, Nakićenović, Nebojša and Rob Swart, editors, Cambridge University Press, Cambridge, UK.

IPCC (2007), *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Metz, Bert, Ogunlade Davidson, Peter Bosch, Rutu Dave and Leo Meyer, editors, Cambridge University Press, Cambridge, UK and New York, NY.

Hertel, Thomas W., editor (1997), "*Global Trade Analysis: Modeling and Applications*," Cambridge University Press, New York.

Hope, Chris (2006), "The Marginal Impact of CO2 from PAGE2002: An Integrated Assessment Model Incorporating the IPCC's Five Reasons for Concern," *The Integrated Assessment Journal*, 6(1), pp. 19–56.

Houser, Trevor, Rob Bradley, Britts Childs, Jacod Werksman, and Robert Heilmayr (2008), *"Leveling the Carbon Playing Field,"* Peterson Institute for International Economics, Washington DC.

Hufbauer, Gary Clyde, Steve Charnovitz and Jisun Kim (2009), "*Global Warming and the World Trading System, Peterson Institute for International Economics*," Washington, DC.

Kehoe, T.J., T.N. Srinivasan, and J. Whalley, (2005), *Frontiers in Applied general Equilibrium Modeling,* Cambridge University Press, Cambridge.

Linnemann, Hans, Pitou Van Dijck, and Harmen Verbruggen (1987), "Export-Oriented Industrialization in Developing Countries," ISBN 9971-69-112-4, Manila.

Lockwood, Ben and John Whalley, (2008), "Carbon Motivated Border Tax Adjustments: Old Wine in Green Bottles?" NBER Working Paper No. 14025.

Manne, Alan, Robert Mendelsohn and Richard Richels (1995), "MERGE: A model for evaluating regional and global effects of GHG reduction policies," *Energy Policy*, 23(1), pp. 17-34.

McKay, Michael D., Conover, William J., and Beckman, Richard J. (1979), "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," *Technometrics*, 21(2), pp. 239-245.

Morris, Harvey, Fiona Harvey, and Geoff Dyer (2009), "Beijing to Spur Energy Efficiency," Available at www.ft.com (accessed September 23, 2009).

Nordhaus, William, (2007), "The Challenge of Global Warming: Economic Models and Environmental Policy in the DICE-2007 Model," manuscript, May 2007.

Panagariya, Arvind, (2009), "Climate Change and India: Implications and Policy Options," mimeo, University of Columbia.

Pauwelyn, Joost (2009), "Testimony Before the Subcommittee on Trade of the House Committee on Ways and Means," March 24, 2009; available at http:// waysandmeans.house.gov/media/ pdf/111/pauw.pdf

Peterson, Everett B. and Joachim Schleich (2007), "Economic and Environmental Effects of Border Tax Adjustments," Working Paper Sustainability and Innovation No. S 1/2007. Fraunhofer Institute

Systems and Innovations Research.

Ponssard, J-P. Walker, N. (2008), “EU Emissions Trading and the cement sector: A spatial competition analysis,” forthcoming in Climate Policy.

Quirion, Philippe and Damien Demailly (2006), "Leakage from climate policies and border tax adjustment: Lessons from a geographic model of the cement industry," Working Papers halshs-00009337_v1, HAL.

Reinaud, Julia (2005), “Industrial Competitiveness under the European Union Emissions Trading Scheme,” International Energy Agency, IEA information Paper.

Rimmer, Maureen T. and Alan A. Powell (1992), “An Implicitly Directly Additive Demand System: Estimates for Australia,” Impact Project Preliminary Working Paper, No. OP-73, October.

Stern, Nicholas Herbert, 2007, The *Economics of Global Climate Change: The Stern Review*. Cambridge UK: Cambridge University Press.

Stern, Nicholas Herbert, 2009, “Transatlantic Perspective on Climate Change and Trade Policy.” Keynote address, Peterson Institute for International Economics, March 4.

Strand, Jon (2009), “Revenue Management Effects Related to Financial Flows Generated by Climate Policy,” WB Policy Research Paper 5053. The World Bank: Washington DC.

Swiler, Laura P. and Gregory D. Wyss (2004). “A User’s Guide to Sandia’s Latin Hypercube Sampling Software: LHS UNIX Library/Standalone Version” *Technical Report* SAND2004-2439, Sandia National Laboratories, Albuquerque, NM.

United Nations (2007), World Population Prospects: The 2006 Revision Population Database, United Nations Population Division, New York, NY, http://esa.un.org/unpp/.

UNDP, 2007/2008, Human Development Report, “Fighting climate change: Human solidarity in a divided world,” New York.

van der Mensbrugghe, Dominique (2006), “Linkage Technical Reference Document,” *processed*, The World Bank.

van der Mensbrugghe, Dominique (2008), “The Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model,” *processed*, the World Bank.

World Trade Organization (2009). “Trade and Climate Change: A Report by the United Nations Environment Program and the World Trade Organization,” Geneva.

World Bank (2009), World Development Report 2010: “Development and Climate Change,” The World Bank: Washington DC.

Table 1: Scenarios on Unilateral Emissions Reductions and Trade Actions (Border Tax Adjustments)

Scenario	Target Emissions Cuts		Basis for Border Tax Adjustment	Product Coverage of Border Tax Adjustment	Treatment of Exports
	High Income	Low and Middle Income			
NBTA17	17% relative to 2005 emission levels	0%	n.a.	n.a.	n.a.
BTAFU	17% relative to 2005 emission levels	0%	Carbon content in imports	All merchandise imports	No rebate for exports
BTADU	17% relative to 2005 emission levels	0%	Carbon content in domestic production	All merchandise imports	No rebate for exports
BTADE	17% relative to 2005 emission levels	0%	Carbon content in domestic production	All merchandise imports	Exporters rebated domestic carbon tax
BTAFR	17% relative to 2005 emission levels	0%	Carbon content in imports	Energy-intensive merchandise imports	No rebate for exports
BTADR	17% relative to 2005 emission levels	0%	Carbon content in domestic production	Energy-intensive merchandise imports	No rebate for exports

Table 2: Competitiveness Effects in Industrial Countries of Unilateral Emissions Reductions

	% Change in Imports of Energy-intensive Manufacturing			% Change in Exports of Energy-intensive Manufacturing			% Change in Output of Energy-intensive Manufacturing		
Scenario	High Income	US	EU	High Income	US	EU	High Income	US	EU
NBTA17	1.3	3.5	3.1	-6.4	-11.6	-5.2	-2.3	-4.4	-1.9
BTAFU	-16.8	-10.1	-38.7	-15.7	-15.9	-21.5	-0.3	-2.5	1.8
BTADU	-6.2	-4.6	-11.3	-8.8	-14.1	-7.8	-1.5	-3.6	-0.5
BTADE	-3.2	-1.1	-7.8	1.4	0.7	4.1	0.0	-0.8	1.0
BTAFR	-20.1	-12.4	-46.7	-4.3	-7.0	-3.2	2.2	-0.5	4.5
BTADR	-7.5	-6.0	-14.9	-6.1	-10.6	-3.9	-0.8	-2.6	0.4

Notes: ***NBTA17:*** *Industrial countries alone reduce emissions by 17% and take no trade policy action;* ***BTAFU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports;* ***BTADU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production;* ***BTADE:*** *Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production;* ***BTAFR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports;* ***BTADR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Table 3: Impact on Emissions Reductions

Scenario	World Total	High Income	US	EU	Low and Middle Income	China	Brazil	India	SSA
% Change in Emissions Relative to Business as Usual (BAU) in 2020									
NBTA17	-9.3	-28.4	-33.5	-30.0	1.0	0.6	1.3	0.8	3.0
BTAFU	-10.9	-28.5	-33.5	-30.0	-1.5	-1.7	0.6	-1.6	0.7
BTADU	-9.8	-28.4	-33.5	-30.0	0.3	0.0	0.8	0.3	2.3
BTADE	-10.0	-28.5	-33.5	-30.0	0.0	-0.3	0.8	-0.2	2.2
BTFAR	-10.6	-28.5	-33.5	-30.0	-1.0	-1.3	0.6	-0.5	1.5
BTADR	-9.8	-28.4	-33.5	-30.0	0.3	0.0	0.6	0.4	2.3
% Change in Emissions Relative to 2005									
NBTA17	56.9	-11.4	-17.0	-17.0	122.5	183.5	37.6	156.5	82.5
BTAFU	54.1	-11.6	-17.0	-17.0	117.2	177.0	36.6	150.3	78.4
BTADU	56.2	-11.5	-17.0	-17.0	121.1	182.0	36.8	155.0	81.4
BTADE	-17.0	-11.5	-17.0	-17.0	120.4	181.2	36.8	153.7	81.1
BTFAR	54.7	-11.5	-17.0	-17.0	118.2	178.3	36.5	153.2	79.9
BTADR	56.2	-11.5	-17.0	-17.0	121.1	181.9	36.6	155.3	81.3

Notes: ***NBTA17:*** *Industrial countries alone reduce emissions by 17% and take no trade policy action;* ***BTAFU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports;* ***BTADU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production;* ***BTADE:*** *Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production;* ***BTAFR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports;* ***BTADR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Table 4. Carbon Intensity by sector (in tons per million US dollars, 2004)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC	High income countries	Low and middle income countries	World total
Direct Intensity																		
Agriculture	40	57	41	45	39	63	82	0	65	24	9	94	44	15	46	45	47	46
All energy	485	879	396	611	609	116	2067	1501	984	665	678	785	456	727	458	642	886	758
All manufacturing	18	36	21	38	36	53	127	111	158	91	127	243	152	65	47	25	107	46
Energy intensive manufacturing	43	90	53	92	98	141	326	283	313	288	735	538	384	159	126	62	279	116
Other manufacturing	7	12	6	8	8	8	35	36	31	34	20	74	50	17	13	8	31	14
Other industries	6	3	6	34	5	18	29	13	30	38	4	62	36	38	25	7	30	13
Service	21	32	16	38	39	63	82	68	171	135	89	213	107	67	73	26	97	36
Total	40	74	34	81	80	78	303	250	385	195	167	383	228	149	114	55	228	92
Total (Direct plus Indirect) Intensity																		
Agriculture	74	141	76	126	112	129	350	301	307	75	104	335	184	72	113	98	223	168
All energy	541	1016	433	735	636	186	2800	1749	1333	752	753	982	582	823	609	729	1147	928
All manufacturing	62	159	79	156	133	168	681	518	848	244	282	712	378	273	144	99	449	187
Energy intensive manufacturing	107	272	140	293	251	286	1163	888	1193	541	1062	1190	746	505	264	172	811	330
Other manufacturing	42	111	51	81	80	107	459	354	568	158	145	437	215	156	92	66	289	122
Other industries	46	69	46	114	77	89	561	287	381	232	218	401	179	240	110	60	342	132
Service	46	94	40	89	100	101	340	231	409	265	160	435	232	161	133	67	242	92
Total	74	153	70	157	155	149	772	535	767	332	281	672	380	281	199	109	479	187

Table 5. Additional Tariff on Exports by Origin

	BTAFU		BTADU		BTADE				BTAFR		BTADR	
					Tariff		Export Rebate					
	All manufacturing	Energy-intensive manufacturing	All manufacturing	Energy-intensive manufacturing	All manufacturing	Energy-intensive manufacturing	All manufacturing	Energy-intensive manufacturing	All manufacturing	Energy-intensive manufacturing	All manufacturing	Energy-intensive manufacturing
Rest of High Income	5.1%	8.7%	3.2%	5.8%	3.3%	6.1%	4.0%	6.8%	1.1%	9.2%	0.7%	5.9%
Brazil	5.8%	9.9%	4.4%	7.1%	4.5%	7.4%	4.3%	6.7%	2.9%	10.4%	2.1%	7.2%
China	26.1%	42.7%	3.1%	6.2%	3.3%	6.5%	3.7%	6.8%	0.5%	44.6%	0.6%	6.3%
India	20.3%	28.5%	3.5%	6.8%	3.6%	7.0%	7.1%	9.8%	1.1%	29.8%	1.0%	6.9%
Russia	35.3%	40.0%	5.2%	6.5%	5.4%	6.7%	3.5%	5.1%	6.7%	42.0%	4.2%	6.6%
Rest of East Asia	9.5%	14.8%	3.1%	5.7%	3.2%	6.0%	3.8%	7.0%	1.1%	15.6%	0.7%	5.7%
Rest of South Asia	10.3%	39.2%	3.0%	5.7%	3.1%	5.9%	3.8%	6.4%	0.2%	41.0%	0.3%	5.8%
Rest of ECA	23.5%	39.7%	4.1%	6.7%	4.2%	6.9%	3.7%	5.5%	2.2%	42.3%	2.2%	6.8%
Middle East and North Africa	16.6%	30.4%	3.2%	6.3%	3.3%	6.5%	4.0%	6.3%	0.7%	32.0%	0.7%	6.4%
Sub-Saharan Africa	10.9%	19.0%	3.9%	6.6%	4.1%	6.8%	3.7%	6.4%	3.0%	20.1%	1.9%	6.7%
Rest of LAC	6.6%	11.8%	4.2%	7.6%	4.4%	8.0%	4.7%	7.7%	1.8%	12.3%	1.3%	7.8%

*Notes: **BTAFU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports; **BTADU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production; **BTADE:** Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production; **BTAFR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports; **BTADR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Table 6: Impact on Welfare, Manufacturing Output, and Exports

Scenario	World Total	High Income	US	EU	Low and Middle Income	China	India	Brazil	SSA
% Change in Welfare									
NBTA17	-0.5	-0.6	-0.6	-0.7	-0.3	-0.2	0.0	-0.1	-0.5
BTAFU	-1.0	-0.4	-0.4	-0.4	-2.4	-3.7	-1.4	-0.5	-1.2
BTADU	-0.6	-0.5	-0.5	-0.5	-0.8	-0.6	-0.3	-0.4	-1.0
BTADE	-0.5	-0.5	-0.6	-0.5	-0.5	-0.3	0.1	-0.3	-0.7
BTAFR	-0.6	-0.5	-0.6	-0.6	-0.8	-0.7	-0.3	-0.3	-0.9
BTADR	-0.5	-0.5	-0.6	-0.6	-0.5	-0.3	-0.1	-0.2	-0.7
% Change in Output of Total Manufacturing									
NBTA17	-0.4	-0.8	-1.2	-0.8	0.1	-0.2	0.1	0.4	0.8
BTAFU	-0.8	0.8	-0.2	1.9	-3.0	-3.6	-3.3	1.5	-0.9
BTADU	-0.5	-0.6	-1.2	-0.3	-0.4	-0.5	-0.4	0.3	0.4
BTADE	-0.4	-0.3	-0.5	0.0	-0.6	-0.5	-0.5	0.0	-0.1
BTAFR	-0.3	-0.4	-1.0	-0.1	-0.2	-0.3	-0.3	0.2	0.1
BTADR	-0.4	-0.7	-1.2	-0.6	0.0	-0.2	0.0	0.1	0.5
% Change in Exports of Total Manufacturing									
NBTA17	-1.0	-1.8	-2.3	-2.1	-0.1	-0.9	-0.3	1.0	2.7
BTAFU	-12.9	-11.3	-10.1	-23.2	-14.8	-20.8	-16.0	1.9	-8.8
BTADU	-4.0	-4.8	-6.5	-6.6	-3.2	-3.4	-3.2	-2.5	-1.8
BTADE	-1.2	-0.5	0.0	0.5	-2.0	-1.8	-2.1	-0.6	-2.0
BTAFR	-3.2	-3.5	-3.7	-5.8	-2.9	-3.2	-3.0	-1.8	-3.6
BTADR	-1.9	-2.6	-3.4	-3.3	-1.2	-1.5	-1.3	-1.8	-0.1

Notes: ***NBTA17:*** *Industrial countries alone reduce emissions by 17% and take no trade policy action;* ***BTAFU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports;* ***BTADU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production;* ***BTADE:*** *Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production;* ***BTAFR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports;* ***BTADR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Technical Appendix: The Model and Numerical Analysis

The results in this paper rely on the World Bank's Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) Model.[21] The ENVISAGE model's core is a relatively standard recursive dynamic global general equilibrium (CGE) model. Incorporated with the core CGE model is a greenhouse gas (GHG) emissions module that is connected to a simple climate module that converts emissions into atmospheric concentrations, radiative forcing and changes in mean global temperature. The climate module has feedback on the economic model through so-called damage functions—currently limited to productivity shocks in agriculture. The combination of the socio-economic CGE model with the climate module is commonly referred to an integrated assessment model (IAM).

ENVISAGE is calibrated to Release 7 of the GTAP dataset with a 2004 base year.[22] It has been used to simulate dynamic scenarios through 2100. For the purposes of this study, 2020 is the terminal year. The 113 countries/regions of GTAP are aggregated to 15 countries/regions for this study and the 57 sectors are aggregated to 21 sectors. Full detail on the aggregation is provided in Appendix Table 1. The GTAP data is supplemented with satellite accounts that include emissions of the so-called Kyoto gases—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydrofluorocarbons (F-gases), different electricity production activities (coal, oil and gas, hydro, nuclear and other), and potential land and hydro supplies.

Within each time period a full equilibrium is achieved given the fixed regional endowments, technology and consumer preferences. Production is modeled as a series of nested constant-elasticity-of-substitution (CES) functions that are designed to reflect the substitution and complementarity of inputs. Unlike many standard models, energy plays a key role as an input and is modeled as a complement to capital in the short-run but a substitute to capital in the long run. This reflects the putty/clay specification of production that incorporates vintage capital. The key assumption is that there is greater substitution across inputs in the long run (i.e. with *new* capital) than in the short run (with *old* or installed) capital. One consequence of this specification is that countries that have higher growth and higher rates of investment typically have a more flexible economy in the aggregate. Thus, all else equal, the same tax on carbon has a lower cost. There is a single representative household that consumes goods and services and saves.[23] The savings rate is partially a function of the demographic structure of the region. Savings rise as either the elderly or youth dependency ratios fall. The government sector is relatively passive. Aggregate expenditures are fixed as a share of total GDP and revenues adjust to maintain fiscal balance (through a lump sum tax on households). Investment is savings driven.

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[21] See van der Mensbrugghe 2008 for full details of the model.

[22] See www.gtap.org.

[23] The model is designed with several different consumer demand specifications including the CDE (see Hertel 1997), the LES/ELES (see van der Mensbrugghe 2006) and the AIDADS (see Rimmer and Powell 1992 and van der Mensbrugghe 2006). For this paper we have used the AIDADS.

Aggregate demand by sector is summed across all domestic agents and represents a composite of domestically produced goods and imports—the so-called Armington aggregate.[24] The aggregate Armington good is allocated between domestic production and imports using a two-nested CES specification. The first nest allocates aggregate demand between domestic production and an aggregate import bundle. The second nest decomposes aggregate imports into import by region of origin. This generates a bilateral trade flow matrix. Domestic producers are assumed to supply both domestic and export markets without friction, i.e. the law of one price holds for domestically produced goods irrespective of their final destination.[25] Bilateral trade is associated with three price wedges. The first wedge reflects differences between producer prices and the border (FOB) price, i.e. an export tax or subsidy. The second wedge reflects international trade and transport margins, i.e. the difference between FOB and CIF prices. The third wedge reflects the difference between the CIF price and the end-user price, i.e. import tariffs. All three wedges are fully bilateral.

Model closure is consistent with long-term equilibrium. As stated above, fiscal balance is maintained through lump sum taxes on households under the assumption of fixed public expenditures (relative to GDP). Changes in revenues, for example carbon tax revenues, imply a net decrease in household direct taxes. Investment is savings driven. This assumption implies that changes in investment are likely to be relatively minor since public and foreign savings are fixed and household savings will be relatively stable relative to income. The third closure rule is that the capital account is balanced. Ex ante changes in the trade balance are therefore offset through real exchange rate effects. A positive rise in net transfers, for example through a cap and trade scheme, would tend to lead to a real exchange rate appreciation.

The model dynamics are relatively straightforward. Population and labor force growth rates are based on the UN population's projection[26]—with the growth in the labor force equated to the growth of the working age population. Investment, as mentioned above, is savings driven and the latter is partially influenced by demographics. Productivity growth in the baseline is 'calibrated' to achieve a target growth path for per capita incomes—differentiated for agriculture, manufacturing and services.

Emissions of GHGs have three drivers. Most are generated through consumption of goods—either in intermediate of final demand—for example the combustion of fossil fuels. Some are driven by the level of factor input—for example methane produced by rice is linked to the amount of cultivated land. And the remainder is generated by aggregate output—for example waste-based methane emissions. The climate module takes as inputs emissions of GHGs and converts them to atmospheric concentration, then radiative forcing and finally temperature change.[27]

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[24] Armington 1969.

[25] Analogously to aggregate domestic demand, the model allows for a two-nested constant-elasticity-of-transformation function to allocate domestic production between domestic and foreign markets.

[26] United Nations 2007.

[27] The climate module is largely derived from the MERGE model, Manne et al 1995.

The temperature change is linked back to the socio-economic model through damage functions. The damage functions—currently limited to agriculture—are calibrated to estimates provided by Cline (2007). His estimates relate to anticipated productivity impacts from a 2.5° C in temperature[28], estimated to occur according to his estimates in 2080. Cline provides two sets of estimates. One set allows for the positive impact of higher concentrations of CO_2 in the atmosphere on plant growth—a so-called carbon fertilization effect. The other excludes this effect. The scientific community is still uncertain about this effect. Greenhouse gas experiments suggest it may be potent. Field experiments suggest otherwise. In our simulations, we use the average of the two estimates.

ENVISAGE has a flexible system of mitigation policies (limited to the moment to CO_2 emissions alone). The simplest is a country or region specific carbon tax—that also allows for exemptions for designated sectors or households. An alternative is to provide a cap on emissions at either a country, regional or global level. The model will then produce the shadow price of carbon, i.e. the carbon tax, as a model outcome. If a global cap is imposed, a single uniform tax will be calculated. This type of regime assumes no trading. A final option is to have a regional or global cap with trading and assigned quotas. Similar to the previous regime, a uniform carbon tax will be calculated (and would be nearly identical to the no-trade carbon tax), but emissions trading would occur depending on the initial quotas and the shape of the individual marginal abatement curves for each member of the trading regime.

One intuitive way to capture the inter-country differences of a carbon tax is the following formula that is derived from a simple partial equilibrium framework:[29]

$$(1) \qquad R = 1 - \left[1 + \frac{\rho.\tau}{P}\right]\sigma \quad \leftrightarrow \tau = \frac{P}{\rho}\left[(1 - R)^{-1/\sigma} - 1\right]$$

In formula (1), τ is the carbon tax, P is the price of energy (for example $ per ton of oil equivalent), ρ is the average carbon content of energy (for example ton of carbon per ton of oil equivalent), σ is the overall elasticity of substitution across factors include energy and R is the level of emissions reduction.[30] The left hand side of the formula shows the level of reduction for a given carbon tax and the right hand side shows the level of the carbon tax for a given reduction level. With R equal to 0, the carbon tax is obviously 0. The formula suggests that the carbon tax is higher (for a given targeted reduction) with higher energy prices, lower carbon content (i.e. cleaner economies) and less flexible economies (i.e. with a low value for σ). This suggests that the carbon tax will be higher on average in developed economies that already have high energy prices and relatively clean energy (for example France and Japan) and have lower savings and therefore more installed and less flexible capital than on average in the rapidly developing economies.

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[28] Which he assumes occurs in the 2080s based on the SRES scenarios (IPCC 2000) and global climate change model (GCM) runs.

[29] See Burniaux et al. 1992.

[30] For example, if energy is priced at $50 per ton of oil equivalent and the average carbon content is 50% and the substitution elasticity is 0.8 and a carbon tax of $150 per ton of carbon is imposed, the level of reduction would be 52 percent.

The implication of this is that on aggregate developed countries will wish to purchase carbon offsets from developing countries in a cap and trade regime where quotas for developed countries are below baseline emissions.

Unilateral action and leakage

One key concern in any carbon regime that excludes major carbon emitters is that production of carbon intense goods will move to countries with no (or a lower) price on carbon. Burniaux and Oliveira Martins (2000) provide a succinct discussion of the main channels of leakage—distinguishing between non-energy and energy markets. On the non-energy side, one of the key channels of course is that the higher cost of production in countries with a carbon tax will lead to a competitive disadvantage and shift production to lower cost countries. The degree of leakage will therefore depend on the tradability of non-energy goods (reflected by the so-called Armington elasticity in most trade models) and on capital mobility. Leakage would increase with tradability as the rise in domestic costs would lead to large substitution effects with rising imports and declining exports. The role of capital mobility is less clear cut and could potentially go in reverse direction (though is closely linked to the Armington elasticity). A drop in international energy prices (particularly oil), could potentially lead to a real exchange rate appreciation for Annex I countries and a capital inflow.

As regards the energy market, the degree of leakage will depend on two effects—how much energy prices drop in non-Annex I countries thus leading to increased energy demand and emissions and the degree of inter-fuel substitution. The energy channels are essentially of three kinds. First there is role of ‘carbon’ supply elasticities. As the price of oil drops internationally, there would be a relative switch to oil away from coal in non-Annex I countries. All else equal, this would tend to reduce leakage as coal is more intensive in carbon. The lower the supply elasticity of oil, the greater the price drop of oil, and the higher the supply elasticity of coal, the more its price is invariant to demand changes and the combination of these two effects would minimize leakage. This would be moderated to some extent by the degree of tradability of coal. A low supply elasticity of coal linked with a highly integrated coal market would induce Annex I coal producers to export considerable volumes to non-Annex I countries. For a variety of reasons, including logistical, this is an unlikely outcome. Another channel is inter-fuel substitutability. Here two effects can offset or reinforce each other—overall demand effect versus substitution effects.

Numerical analysis

It is difficult to undertake systematic sensitivity analysis with a full-blown CGE model. An alternative approach is to reduce the model to some core set of relations that capture the essence of the full model and that is amenable to systematic sensitivity analysis. This is the approach taken by Burniaux and Oliviera Martins, which we have attempted to replicate though with some modifications. We have re-constructed their model, but have converted it to a model in levels rather than linearized in percent deviation. Second, we have calibrated the model to the same database as the ENVISAGE model with a 2004 base instead of the 1985 database. Third, rather than replicate their pair-wise sensitivity analysis, that clearly illustrates the impacts of the various channels, we take a probabilistic approach that assumes some probability distribution for each of the uncertain key parameters.

The stochastic approach we take is the same as used by Hope (2006) with the PAGE2002 model and that underscored many of the numerical results in the Stern Review (2007). The approach uses a technique called Latin Hypercube Sampling (LHS).[31] It is a restricted form of Monte Carlo simulation where the multivariate sampling is done from a limited number of observations but whose statistical properties match closely those that would be generated from full Monte Carlo sampling. The resulting sample (of 10,000 in our case) of the key parameter values are used in the reduced form model and generate a distribution of the leakage rates. Table 1c shows the list of the key parameters in the reduced form model[32] with the mode value. The mode variable corresponds roughly with the parameter values in the full ENVISAGE Model. Each parameter is assigned a triangular distribution that covers the assumed range of the parameter.

Appendix Figure 1 depicts the frequency distribution generated by the sampling exercise. The policy shock is a 28 percent reduction in Annex I emissions (corresponding to the 17 percent reduction target relative to 2005 that translates into a 28 percent reduction relative to 2020 baseline values). The mean leakage rate using the reduced form model is 11 percent with a standard deviation of 5 percent. A little over 1 percent of the sample exhibited a leakage rate of below zero and 94 percent of the sample fell between a leakage rate of 0 and 20 percent.

The leakage rate generated by ENVISAGE is considerably lower than the mean of 11 percent. There are a number of potential causes that need further exploration. First, the production structure in ENVISAGE is different from that in the maquette as we tailored it more to the Burniaux and Oliveira Martins model and not to ENVISAGE. Second, the data calibration could be impacting some of the key relations—across fuels and with the emission coefficients. Third, there might be strong compositional effects—both across regions and across sectors that would affect the overall impact on the leakage rate.
In the literature there a not a plethora of leakage estimates—and they are hard to compare in any case: a) because the nature of the shock is different (e.g. many of the earlier estimates focused on the potential leakage effects from the Kyoto Protocol) b) different model base years and baselines; and c) different model specifications and key elasticities. Burniaux and Oliveira Martins cite a range of leakage rates with respect to the Kyoto Protocol of between 2 and 21 percent. Fischer and Fox (2009) provide some leakage rates at the sectoral level that range from 8 percent to 64 percent from a simulation of the imposition of a carbon tax of $50/tC. Again the comparison with the results discussed herein is difficult as the nature of the model and the shock is quite different. The paper is also silent on the relative fossil fuel supply elasticities that appear to be so crucial. Babiker (2005) focuses on the leakage effects from the Kyoto Protocol. The leakage effects range from around 25 to over 100 percent, albeit the model assumes a low coal supply elasticity (0.5). The paper is interesting because it shows the sensitivity of the

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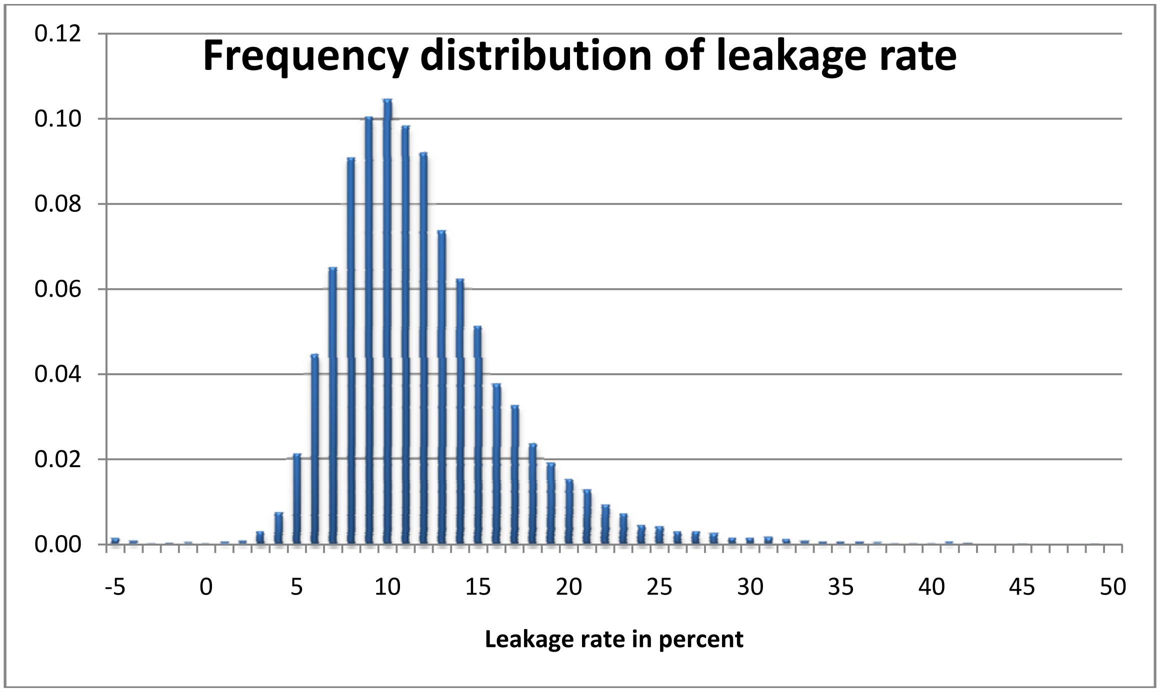
[31] See McKay et al. (1979) and Swiler and Wyss (2004).

[32] Details of the reduced-form model are available from the authors.

leakage rate to two key assumptions—the tradability of goods (comparing an Armington model with a Hecksher-Ohlin specification) and constant versus increasing rates of return. Burniaux and Oliveira Martins suggest that the tradability parameter has relatively little impact on the leakage rate and given the high Armington elasticities we are using, one wouldn't expect a large effect from moving to a Hecksher-Ohlin specification. However, Babiker demonstrates that this no longer holds true with increasing returns to scale. Given the wide range of uncertainty, it would appear that this issue would benefit from a more detailed study comparing leakage rates across models with some initial harmonization on key assumptions and then exploring alternatives.

Appendix Figure 1



Appendix Table 1a: Regional dimensions of ENVISAGE[a]

1	eur	EU27 with EFTA Austria (aut), Belgium (bel), Cyprus (cyp), Czech Republic (cze), Denmark (dnk), Estonia (est), Finland (fin), France (fra), Germany (deu), Greece (grc), Hungary (hun), Ireland (irl), Italy (ita), Latvia (lva), Lithuania (ltu), Luxembourg (lux), Malta (mlt), Netherlands (nld), Poland (pol), Portugal (prt), Slovakia (svk), Slovenia (svn), Spain (esp), Sweden (swe), United Kingdom (gbr), Switzerland (che), Norway (nor), Rest of EFTA (xef), Bulgaria (bgr), Romania (rou)
2	usa	United States
3	jpn	Japan
4	kor	Korea
5	rha	Rest of high income Annex 1 Australia (aus), New Zealand (nzl), Canada (can)
6	rhy	Rest of high income Hong Kong (hkg), Taiwan (twn), Singapore (sgp)
6	bra	Brazil
7	chn	China
8	ind	India
9	rus	Russia
10	xea	Rest of East Asia Rest of Oceania (xoc), Rest of East Asia (xea), Cambodia (khm), Laos (lao), Myanmar (mmr), Viet Nam (vnm), Indonesia (idn), Malaysia (mys), Philippines (phl), Thailand (tha), Bangladesh (bgd), Pakistan (pak)
11	xsa	Rest of South Asia Rest of Southeast Asia (xse), Sri Lanka (lka), Rest of South Asia (xsa)
12	xec	Rest of Europe and Central Asia Albania (alb), Belarus (blr), Croatia (hrv), Ukraine (ukr), Rest of Eastern Europe (xee), Rest of Europe (xer), Kazakhstan (kaz), Kyrgystan (kgz), Rest of Former Soviet Union (xsu), Armenia (arm), Azerbaijan (aze), Georgia (geo)
13	mna	Middle East and North Africa Iran (irn), Turkey (tur), Rest of Western Asia (xws), Egypt (egy), Morocco (mar), Tunisia (tun), Rest of North Africa (xnf)
14	ssa	Sub-Saharan Africa Nigeria (nga), Senegal (sen), Rest of Western Africa (xwf), Central Africa (xcf), South-Central Africa (xac), Ethiopia (eth), Madagascar (mdg), Malawi (mwi), Mauritius (mus), Mozambique (moz), Tanzania (tza), Uganda (uga), Zambia (zmb), Zimbabwe (zwe), Rest of Eastern Africa (xec), Botswana (bwa), South Africa (zaf), Rest of South African Customs Union (xsc)
15	xlc	Rest of Latin America and the Caribbean Mexico (mex), Rest of North America (xna), Argentina (arg), Bolivia (bol), Chile (chl), Colombia (col), Ecuador (ecu), Paraguay (pry), Peru (per), Uruguay (ury), Venezuela (ven), Rest of South America (xsm), Costa Rica (cri), Guatemala (gtm), Nicaragua (nic), Panama (pan), Rest of Central America (xca), Caribbean (xcb)

Note(s): a) Aggregate regions indicate relevant GTAP countries/regions with GTAP code in parenthesis.

Appendix Table 1b: Sectoral dimensions of ENVISAGE[a]

1	cop	Crops Paddy rice (pdr), Wheat (wht), Cereal grains, n.e.s. (gro), Vegetables and fruits (v_f), Oil seeds (osd), Sugar cane and sugar beet (c_b), Plant-based fibers (pfb), Crops, n.e.s. (ocr)
2	lvs	Livestock Bovine cattle, sheep and goats, horses (ctl), Animal products n.e.s. (oap), Raw milk (rmk), Wool, silk-worm cocoons (wol)
3	frs	Forestry
4	coa	Coal
5	oil	Crude oil
6	gas	Natural gas
7	omn	Other mining
8	pfd	Processed food Fishing (fsh), Bovine cattle, sheep and goat, horse meat products (cmt), Meat products n.e.s. (omt), Vegetable oils and fats (vol), Dairy products (mil), Processed rice (pcr), Sugar (sgr), Food products n.e.s. (ofd), Beverages and tobacco products (b_t)
9	p_c	Refined oil
10	crp	Chemicals rubber and plastics
11	ppp	Paper products, publishing
12	nmm	Mineral products n.e.s.
13	i_s	Ferrous metals
14	nfm	Metals n.e.s.
15	tre	Transport equipment Motor vehicles and parts (mvh), Transport equipment n.e.s. (otn)
16	mnu	Other manufacturing Textiles (tex), Wearing apparel (wap), Leather products (lea), Wood products (lum), Metal products (fmp), Electronic equipment (ele), Machinery and equipment n.e.s. (ome), Manufactures n.e.s. (omf)
17	ely	Electricity[b]
18	gdt	Gas distribution
19	cns	Construction
20	trp	Transport services Transport n.e.s. (otp), Sea transport (wtp), Air transport (atp)
21	osv	Other services Water (wtr), Trade (trd), Communication (cmn), Financial services n.e.s. (ofi), Insurance (isr), Business services n.e.s. (obs), Recreation and other services (ros), Public administration and defence, education, health services (osg), Dwellings (dwe)

Note(s):

a) Aggregate sectors indicate relevant GTAP sectors with GTAP code in parenthesis.

b) Electricity is a single consumed and traded commodity. However, in each region/country it is produced by multiple activities that include coal and gas power plants, hydro-electricity, nuclear and other (mainly renewable) technologies.

Appendix Table 1c: Key elasticities with reference bounds

		Annex I			Non-Annex I		
		Minimum	*Mode*	*Maximum*	*Minimum*	*Mode*	*Maximum*
Production substitution elasticities							
σ^{p}	Energy-value added	0.2	0.4	1.2	0.2	0.4	1.2
σ^{e}	Inter-fuel	0.5	0.6	3.0	0.5	0.8	3.0
σ^{v}	Capital-labor	0.3	0.8	1.2	0.6	1.0	1.2
Energy supply elasticities							
ε^{coal}	Coal	0.0	5.0	20.0	0.0	5.0	20.0
ε^{oil}	Oil	0.0	1.5	3.0	0.0	1.5	3.0
$\varepsilon^{Other\text{-}energy}$	Lower carbon energy	0.0	1.5	3.0	0.0	1.5	3.0
Armington trade elasticities							
$\sigma^{Non\text{-}energy}$	Non-energy good	1.5	4.0	8.0	1.5	4.0	8.0
σ^{coal}	Coal	2.0	5.0	10.0	2.0	5.0	10.0
$\sigma^{Other\text{-}energy}$	Lower carbon energy	1.5	4.0	8.0	1.5	4.0	8.0
International mobility of capital							
ω^{k}	Transformation elasticity	0.0	1.0	20.0			

Appendix Table 2. Emissions Reductions (percent)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC	High income countries	Low and middle income countries	World total
Relative to Business as Usual (BAU) in 2020																		
NBTA17	-30.0	-33.5	-15.8	-34.4	1.7	1.3	0.6	0.8	0.6	1.6	1.2	1.2	1.7	3.0	1.6	-28.4	1.0	-9.3
BTAFU	-30.0	-33.5	-15.8	-34.4	0.9	0.6	-1.3	-0.5	-0.9	0.1	-1.3	-2.2	-2.0	1.5	0.6	-28.5	-1.0	-10.6
BTADU	-30.0	-33.5	-15.8	-34.4	0.6	0.8	-0.3	-0.2	-0.1	0.9	-0.2	-0.4	0.0	2.2	0.8	-28.5	0.0	-10.0
BTADE	-30.0	-33.5	-15.8	-34.4	0.6	0.8	-0.3	-0.2	-0.1	0.9	-0.2	-0.4	0.0	2.2	0.8	-28.5	0.0	-10.0
BTAFR	-30.0	-33.5	-15.8	-34.4	1.1	0.6	0.0	0.4	0.1	1.0	0.4	0.1	0.5	2.3	1.0	-28.4	0.3	-9.8
BTADR	-30.0	-33.5	-15.8	-34.4	0.2	0.6	-1.7	-1.6	-1.4	0.0	-1.6	-2.1	-2.4	0.7	-0.3	-28.5	-1.5	-10.9
Relative to 2005																		
NBTA17	-17.0	-17.0	-17.0	-17.0	74.2	37.6	183.5	156.5	125.3	74.4	121.7	124.6	35.3	82.5	73.3	-11.4	122.5	56.9
BTAFU	-17.0	-17.0	-17.0	-17.0	71.7	36.6	177.0	150.3	120.8	71.6	115.7	117.4	29.8	78.4	70.1	-11.6	117.2	54.1
BTADU	-17.0	-17.0	-17.0	-17.0	74.2	37.6	183.5	156.5	125.3	74.4	121.7	124.6	35.3	82.5	73.3	-11.4	122.5	56.9
BTADE	-17.0	-17.0	-17.0	-17.0	73.1	36.8	182.0	155.0	124.3	73.4	120.5	122.5	33.8	81.4	71.7	-11.5	121.1	56.2
BTAFR	-17.0	-17.0	-17.0	-17.0	72.8	36.5	178.3	153.2	121.9	71.8	116.4	117.1	30.4	79.9	71.5	-11.5	118.2	54.7
BTADR	-17.0	-17.0	-17.0	-17.0	72.4	36.8	181.2	153.7	123.7	73.1	118.8	121.1	33.0	81.1	72.0	-11.5	120.4	55.8

*Notes: **NBTA17:** Industrial countries alone reduce emissions by 17% and take no trade policy action; **BTAFU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports; **BTADU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production; **BTADE:** Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production; **BTAFR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports; **BTADR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Appendix Table 3. Emissions Tax in dollars per ton carbon

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC	High income countries	Low and middle income countries	World total
NBTA17	332.8	248.7	246.6	218.1	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	241.1	n.a.	66.6
BTAFU	318.1	245.0	238.9	215.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	234.8	n.a.	66.0
BTADU	330.0	247.2	247.7	218.4	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	239.9	n.a.	66.6
BTADE	339.7	257.1	256.9	237.9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	249.3	n.a.	69.3
BTAFR	345.4	252.7	257.0	225.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	248.1	n.a.	69.5
BTADR	337.4	250.8	249.7	221.5	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	244.0	n.a.	67.7

*Notes: **NBTA17:** Industrial countries alone reduce emissions by 17% and take no trade policy action; **BTAFU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports; **BTADU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production; **BTADE:** Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production; **BTAFR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports; **BTADR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Appendix Table 4. Change in Welfare by region (percent)

Scenarios	Unilateral Reductions					
↓Countries/Regions→	NBTA17	BTAFU	BTADU	BTADE	BTAFR	BTADR
EU27 with EFTA	-0.7	-0.4	-0.5	-0.5	-0.6	-0.6
United States	-0.6	-0.4	-0.5	-0.6	-0.6	-0.6
Japan	-0.2	-0.1	-0.1	-0.2	-0.2	-0.2
Rest of high income Annex 1	-0.9	-1.0	-0.8	-1.1	-0.9	-0.9
Rest of high income	-0.1	-0.5	-0.5	-0.1	-0.3	-0.2
Brazil	-0.1	-0.5	-0.4	-0.3	-0.3	-0.2
China	-0.2	-3.7	-0.6	-0.3	-0.7	-0.3
India	0.0	-1.4	-0.3	0.1	-0.3	-0.1
Russia	-1.1	-3.6	-1.7	-1.7	-1.8	-1.4
Rest of East Asia	-0.4	-1.3	-0.9	-0.6	-0.8	-0.6
Rest of South Asia	-0.3	-0.6	-0.4	-0.3	-0.4	-0.3
Rest of ECA	-0.3	-2.3	-0.9	-0.8	-1.5	-0.7
Middle East and North Africa	-0.1	-2.4	-0.7	0.0	-0.6	-0.3
Sub-Saharan Africa	-0.5	-1.2	-1.0	-0.7	-0.9	-0.7
Rest of LAC	-0.7	-1.8	-1.4	-0.8	-1.1	-0.9
High income countries	-0.6	-0.4	-0.5	-0.5	-0.5	-0.5
Low and middle income countries	-0.3	-2.4	-0.8	-0.5	-0.8	-0.5
World total	-0.5	-1.0	-0.6	-0.5	-0.6	-0.5

Notes: ***NBTA17:*** *Industrial countries alone reduce emissions by 17% and take no trade policy action;* ***BTAFU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports;* ***BTADU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production;* ***BTADE:*** *Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production;* ***BTAFR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports;* ***BTADR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Appendix Table 5. Change in Output by sector (percent)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC	High income countries	Low and middle income countries	World total
NBTA17																		
Agriculture	-0.6	-1.0	-0.1	1.0	0.1	-1.2	0.1	0.0	0.2	0.1	0.0	-0.3	-0.1	0.0	0.2	-0.5	0.0	-0.2
All energy	-7.8	-14.8	-3.0	-9.2	2.6	1.0	0.6	0.7	-0.2	0.2	0.2	0.7	1.5	-1.1	-2.2	-9.3	0.0	-4.2
All manufacturing	-0.8	-1.2	-0.8	-0.9	-0.1	0.4	-0.2	0.1	2.0	0.1	-0.1	0.3	-0.3	0.8	1.1	-0.8	0.1	-0.4
Energy intensive manufacturing	-1.9	-4.4	-1.8	-5.9	2.5	2.1	1.2	1.8	5.2	3.0	2.2	3.9	3.2	3.2	3.2	-2.3	2.1	-0.5
Other manufacturing	-0.3	0.4	-0.3	2.4	-1.2	-0.4	-0.9	-0.7	0.2	-0.9	-0.7	-1.8	-1.5	-0.3	0.0	-0.1	-0.8	-0.4
Other industries	-0.3	-1.3	-0.3	-2.5	0.1	0.0	0.0	0.1	-0.5	-0.2	-0.2	0.1	0.0	-0.2	-0.2	-0.7	-0.1	-0.4
Service	-0.5	-0.3	0.0	-0.6	0.2	0.0	0.0	0.0	-0.4	0.2	0.1	0.0	0.1	0.0	0.0	-0.3	0.0	-0.2
Total	-0.8	-1.2	-0.3	-1.4	0.2	0.1	-0.1	0.1	0.2	0.1	0.0	0.2	0.0	0.1	0.2	-0.8	0.0	-0.5
BTAFU																		
Agriculture	-3.2	-8.9	-0.4	-10.2	1.2	-4.0	4.0	0.3	2.7	1.1	0.2	2.2	2.2	1.4	0.7	-5.5	1.6	-1.4
All energy	-8.2	-15.0	-1.6	-9.8	0.7	0.5	-0.7	-0.5	-1.7	-0.5	-1.0	-0.9	0.3	-0.3	-8.2	-9.6	-1.9	-5.4
All manufacturing	1.9	-0.2	-0.5	3.1	-0.8	1.5	-3.6	-3.3	0.6	-1.9	-3.0	-4.8	-8.8	-0.9	1.9	0.8	-3.0	-0.8
Energy intensive manufacturing	1.8	-2.5	-1.5	-1.0	-2.2	1.5	-0.8	-1.6	-2.6	-2.3	-3.5	-7.2	-5.6	-1.9	1.4	-0.3	-1.4	-0.7
Other manufacturing	1.9	0.8	0.0	5.9	-0.2	1.4	-5.0	-4.2	2.5	-1.7	-2.9	-3.5	-9.8	-0.4	2.1	1.3	-3.8	-0.8
Other industries	-0.5	-1.5	-0.6	-2.9	-0.4	-0.9	-3.1	-1.2	-3.0	-1.6	-0.2	-3.2	-2.4	-3.1	-1.8	-1.0	-2.5	-1.6
Service	-1.1	-0.4	-0.1	-1.0	0.3	0.1	-0.4	0.4	-0.9	1.3	0.9	1.7	2.5	0.3	-0.1	-0.6	0.4	-0.4
Total	-0.3	-1.2	-0.3	-1.1	-0.2	0.1	-2.2	-1.3	-0.8	-0.6	-0.7	-1.1	-2.5	-0.3	-0.4	-0.6	-1.5	-0.9
BTADU																		
Agriculture	-0.9	-2.9	0.0	-2.0	0.8	-0.8	0.8	0.1	0.7	0.5	0.1	0.2	0.3	0.4	1.1	-1.6	0.4	-0.4
All energy	-7.4	-14.7	-2.6	-8.9	2.0	0.0	0.2	0.6	-0.7	0.2	0.0	-0.2	1.1	-1.2	-4.3	-9.1	-0.7	-4.5
All manufacturing	-0.3	-1.2	-0.7	0.0	-0.8	0.3	-0.5	-0.4	2.0	-0.6	-1.0	-0.6	-1.9	0.4	0.7	-0.6	-0.4	-0.5
Energy intensive manufacturing	-0.5	-3.6	-1.6	-3.9	0.8	0.6	0.2	0.7	3.1	1.1	1.3	0.4	0.4	1.5	1.8	-1.5	0.7	-0.6
Other manufacturing	-0.2	0.0	-0.3	2.7	-1.5	0.2	-0.9	-0.9	1.4	-1.2	-1.6	-1.1	-2.7	-0.1	0.1	-0.2	-0.9	-0.5
Other industries	-0.2	-1.3	-0.2	-2.5	-0.4	-0.5	-0.5	-0.2	-1.1	-0.8	-0.4	-0.9	-0.8	-0.9	-1.1	-0.7	-0.6	-0.7
Service	-0.6	-0.3	0.0	-0.7	0.4	0.0	-0.1	0.1	-0.5	0.5	0.3	0.2	0.6	0.0	0.1	-0.4	0.1	-0.3
Total	-0.7	-1.2	-0.3	-1.3	-0.1	0.0	-0.3	-0.1	0.0	-0.2	-0.2	-0.2	-0.5	-0.1	-0.3	-0.8	-0.2	-0.6
BTADE																		
Agriculture	-0.4	-1.0	0.4	-0.7	-0.2	-0.8	0.3	0.0	0.5	0.0	-0.2	-0.1	-0.5	0.0	0.2	-0.6	0.0	-0.2
All energy	-6.1	-12.6	-2.3	-6.4	0.0	-1.0	-0.6	-0.5	-1.2	-0.9	-1.2	-1.7	-1.1	-2.1	-4.1	-7.8	-1.5	-4.3
All manufacturing	0.0	-0.5	-0.5	1.0	-1.9	0.0	-0.5	-0.5	1.0	-0.8	-1.1	-1.6	-2.2	-0.1	0.2	-0.3	-0.6	-0.4
Energy intensive manufacturing	1.0	-0.8	-0.6	3.8	-3.2	-1.2	-1.1	-1.7	0.4	-2.6	-1.9	-3.7	-4.2	-1.3	-1.4	0.0	-1.6	-0.6
Other manufacturing	-0.4	-0.4	-0.5	-0.8	-1.3	0.6	-0.2	0.0	1.3	-0.2	-0.9	-0.3	-1.5	0.4	1.0	-0.5	-0.1	-0.4
Other industries	-0.2	-1.2	-0.2	-0.2	-0.5	-0.4	-0.4	-0.3	-1.1	-0.8	-0.3	-0.9	-0.6	-0.4	-0.7	-0.5	-0.5	-0.5
Service	-0.7	-0.5	0.0	-1.3	1.0	0.2	0.3	0.5	-0.4	1.1	0.6	1.0	1.3	0.5	0.6	-0.5	0.5	-0.2
Total	-0.6	-1.0	-0.2	-0.9	-0.4	-0.1	-0.2	-0.1	-0.3	-0.2	-0.3	-0.5	-0.4	0.0	-0.2	-0.7	-0.2	-0.6
BTAFR																		
Agriculture	-1.5	-2.3	-0.3	-1.7	0.5	-0.5	0.9	0.1	1.4	0.4	0.1	1.0	0.7	0.8	1.1	-1.6	0.6	-0.3
All energy	-7.7	-14.9	-2.4	-9.6	1.4	0.0	-0.9	-0.1	-0.3	-0.7	-1.3	-1.1	-1.0	-1.3	-2.8	-9.4	-1.0	-4.8
All manufacturing	-0.1	-1.0	-0.7	0.3	-0.1	0.2	-0.3	-0.3	-0.2	-0.1	-0.1	-1.7	-1.2	0.1	0.9	-0.4	-0.2	-0.3
Energy intensive manufacturing	4.5	-0.5	1.2	1.6	-0.2	-0.4	-3.9	-2.2	-6.2	-3.5	-3.4	-11.2	-7.4	-2.5	-0.5	2.2	-3.7	-0.3
Other manufacturing	-2.4	-1.3	-1.6	-0.5	-0.1	0.5	1.6	0.6	3.2	1.1	0.7	3.7	0.9	1.4	1.6	-1.7	1.4	-0.4
Other industries	-0.3	-1.2	-0.3	-2.4	-0.1	-0.3	-0.7	-0.2	-1.5	-0.8	-0.4	-2.1	-0.5	0.0	-0.7	-0.7	-0.6	-0.7
Service	-0.6	-0.3	0.0	-0.7	0.2	0.0	-0.1	0.0	-0.5	0.4	0.2	0.4	0.4	0.0	0.0	-0.4	0.0	-0.3
Total	-0.7	-1.2	-0.3	-1.3	0.1	0.0	-0.3	-0.1	-0.4	0.0	-0.1	-0.7	-0.3	0.0	0.0	-0.8	-0.2	-0.6
BTADR																		
Agriculture	-1.0	-1.6	-0.2	-0.2	0.4	-0.4	0.4	0.1	0.6	0.3	0.0	0.1	0.2	0.3	0.8	-1.0	0.3	-0.3
All energy	-7.8	-14.8	-2.8	-9.4	1.8	0.4	0.1	0.4	-0.2	-0.2	-0.3	0.1	0.6	-1.2	-2.2	-9.4	-0.3	-4.4
All manufacturing	-0.6	-1.2	-0.8	-0.5	-0.2	0.1	-0.2	0.0	1.4	0.0	-0.1	-0.3	-0.6	0.5	0.8	-0.7	0.0	-0.4
Energy intensive manufacturing	0.4	-2.6	-1.1	-2.4	0.3	-0.3	-0.4	0.3	1.7	-0.1	0.4	-1.0	-0.6	0.6	0.3	-0.8	-0.1	-0.5
Other manufacturing	-1.0	-0.5	-0.6	0.8	-0.4	0.3	-0.1	-0.2	1.3	0.0	-0.2	0.1	-0.6	0.5	1.1	-0.7	0.1	-0.4
Other industries	-0.3	-1.2	-0.2	-2.5	-0.2	-0.1	-0.2	0.0	-0.8	-0.5	-0.3	-0.7	-0.2	-0.1	-0.6	-0.7	-0.3	-0.5
Service	-0.5	-0.3	0.0	-0.6	0.2	0.0	0.0	0.0	-0.4	0.3	0.1	0.1	0.3	0.0	0.0	-0.3	0.0	-0.2
Total	-0.8	-1.2	-0.3	-1.3	0.1	0.0	-0.1	0.0	0.0	0.0	0.0	-0.1	-0.1	0.0	0.1	-0.8	0.0	-0.6

Notes: ***NBTA17:*** *Industrial countries alone reduce emissions by 17% and take no trade policy action;* ***BTAFU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports;* ***BTADU:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production;* ***BTADE:*** *Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production;* ***BTAFR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports;* ***BTADR:*** *Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Appendix Table 6. Change in Exports by sector (percent)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC	High income countries	Low and middle income countries	World total
NBTA17																		
Agriculture	-4.0	-1.7	-2.5	1.0	-1.9	-3.1	-1.3	-0.3	3.4	-2.1	-0.9	-0.8	-2.0	0.2	-0.8	-1.5	-1.9	-1.6
All energy	-8.3	-19.0	-2.9	-5.9	9.1	-1.9	-0.2	6.3	-6.0	-3.2	-3.2	-2.8	-9.5	-3.1	-8.2	-9.4	-5.1	-6.1
All manufacturing	-2.1	-2.3	-2.0	-2.0	-0.6	1.0	-0.9	-0.3	7.1	-0.3	-0.9	0.4	-0.9	2.7	3.2	-1.8	-0.1	-1.0
Energy intensive manufacturing	-5.2	-11.6	-6.5	-11.5	3.7	7.6	6.7	6.4	11.5	5.0	6.5	5.5	5.6	8.3	11.5	-6.4	7.0	-0.7
Other manufacturing	-0.6	1.6	-0.8	4.7	-1.7	-2.0	-2.3	-2.7	1.1	-1.6	-2.0	-3.4	-2.8	-1.4	-0.1	0.0	-2.1	-1.0
Other industries	-0.8	-0.2	-0.8	-10.4	-2.3	1.6	0.3	1.5	1.7	0.6	0.3	0.0	0.8	1.9	4.4	-3.5	1.5	-0.5
Service	-1.5	-1.8	0.6	0.3	0.0	1.6	1.5	-1.4	7.6	3.4	2.5	2.3	0.8	2.2	6.8	-1.1	1.8	0.0
Total	-2.2	-2.7	-1.8	-2.3	-0.4	-0.4	-0.7	-0.2	-0.8	-0.3	-0.6	0.0	-0.5	0.0	-0.6	-2.0	-0.5	-1.3
BTAFU																		
Agriculture	-31.6	-18.6	-21.8	-17.4	-10.9	-10.8	31.0	25.7	20.7	-4.5	-2.7	11.2	6.3	3.0	-5.7	-20.2	-3.8	-16.3
All energy	-35.0	-33.0	-27.5	-11.1	6.3	-4.1	-1.0	13.8	-7.2	-2.9	-2.8	-2.8	-0.7	-2.1	-18.0	-23.9	-8.2	-11.9
All manufacturing	-23.2	-10.1	-13.2	2.8	-1.7	1.9	-20.8	-16.0	-14.3	-4.8	-9.3	-13.7	-20.2	-8.8	2.1	-11.3	-14.8	-12.9
Energy intensive manufacturing	-21.5	-15.9	-20.9	-6.9	-7.6	-2.2	-16.6	-9.7	-19.7	-8.4	-22.3	-15.5	-15.3	-12.3	-4.5	-15.7	-13.0	-14.6
Other manufacturing	-24.0	-7.8	-11.1	9.5	-0.1	3.7	-21.6	-18.3	-6.9	-4.0	-7.4	-12.3	-21.6	-6.2	4.8	-9.5	-15.3	-12.4
Other industries	-20.1	-8.8	-7.8	-16.5	-6.1	-8.1	-2.1	-3.2	3.6	-6.0	2.9	-14.1	1.2	-19.8	0.8	-15.9	-4.3	-9.0
Service	-15.8	-10.4	-5.0	-7.4	5.1	9.4	46.3	25.3	35.1	17.7	16.8	29.0	22.6	14.1	16.3	-9.7	25.6	3.9
Total	-21.8	-11.8	-12.5	-3.5	-0.5	-2.4	-15.8	-6.5	-6.7	-2.6	-3.3	-6.0	-7.3	-3.1	-4.0	-12.0	-8.4	-10.2
BTADU																		
Agriculture	-10.8	-6.2	-5.6	-3.9	-2.3	-2.3	-1.0	1.7	6.9	-1.8	0.3	1.4	-2.0	1.3	0.2	-6.3	-1.1	-5.1
All energy	-14.0	-28.2	-3.0	-7.8	7.6	-5.6	-0.2	10.7	-6.5	-3.1	-3.0	-3.9	-8.7	-3.4	-11.1	-14.5	-6.3	-8.2
All manufacturing	-6.6	-6.5	-3.4	-1.3	-2.4	-2.5	-3.4	-3.2	3.0	-2.3	-4.2	-2.4	-4.9	-1.8	-2.5	-4.8	-3.2	-4.0
Energy intensive manufacturing	-7.8	-14.1	-8.7	-10.0	-0.9	-4.2	-3.3	-0.7	2.8	-0.4	0.6	-1.2	-1.6	0.5	-0.4	-8.8	-1.4	-5.7
Other manufacturing	-5.9	-3.4	-1.9	4.7	-2.8	-1.8	-3.5	-4.1	3.2	-2.7	-4.9	-3.3	-5.9	-3.6	-3.3	-3.2	-3.7	-3.5
Other industries	-5.7	-2.5	-2.3	-12.6	-2.0	-0.6	-1.6	0.6	1.9	-0.2	-0.1	-1.8	-0.9	-1.5	4.5	-6.8	0.1	-2.7
Service	-5.2	-4.8	-0.8	-2.9	3.4	6.8	6.9	3.3	13.2	7.9	6.9	7.5	5.2	6.6	14.3	-3.3	6.8	0.6
Total	-6.6	-6.9	-3.1	-3.2	-1.4	-2.1	-2.7	-1.4	-2.1	-1.4	-1.9	-1.4	-2.0	-1.3	-3.8	-5.0	-2.2	-3.6
BTADE																		
Agriculture	-3.3	-1.9	-6.9	-0.7	-4.3	-3.0	-2.4	-4.1	6.6	-2.8	-3.6	-0.7	-6.2	-0.4	-0.8	-1.9	-2.6	-2.0
All energy	-0.5	-1.8	-6.1	-4.4	2.6	-9.2	-4.4	-3.3	-6.8	-4.6	-4.6	-6.0	-9.7	-3.4	-8.2	-2.0	-6.2	-5.2
All manufacturing	0.5	0.0	-1.7	3.5	-2.8	-0.6	-1.8	-2.1	1.8	-1.7	-3.4	-3.2	-4.3	-2.0	0.6	-0.5	-2.0	-1.2
Energy intensive manufacturing	4.1	0.7	-2.6	9.6	-5.8	-6.0	-7.0	-6.4	-0.4	-5.9	-8.7	-5.9	-8.6	-5.3	-4.8	1.4	-6.3	-1.9
Other manufacturing	-1.2	-0.3	-1.5	-0.8	-2.0	1.9	-0.9	-0.6	5.0	-0.6	-2.6	-1.2	-3.1	0.5	2.8	-1.2	-0.8	-1.0
Other industries	-2.5	0.7	-3.0	-0.5	-2.2	-2.4	-2.3	-5.5	4.2	-1.5	-0.7	-0.9	-3.7	0.5	2.9	-1.5	-1.6	-1.5
Service	-6.6	-8.5	-0.9	-8.2	6.0	13.2	11.0	6.9	19.7	12.5	10.3	13.3	7.8	12.3	19.0	-4.8	10.6	1.1
Total	-1.6	-1.8	-1.7	0.4	-1.3	-1.4	-1.0	-0.7	-2.2	-0.7	-0.9	-1.7	-1.0	-0.5	-0.8	-1.4	-1.0	-1.2
BTAFR																		
Agriculture	-9.2	-4.2	-4.6	-2.8	-1.9	-1.6	2.5	4.2	15.4	-0.3	-2.1	4.8	0.6	4.9	2.2	-4.6	0.6	-3.4
All energy	-11.9	-23.4	-5.3	-9.9	7.4	-3.9	2.5	6.2	-2.9	-4.0	-4.4	-0.2	-9.0	-3.0	-8.5	-13.3	-4.4	-6.5
All manufacturing	-5.8	-3.7	-4.4	-0.1	-1.0	-1.8	-3.2	-3.0	-9.9	-1.1	-1.7	-5.5	-3.5	-3.6	-0.3	-3.5	-2.9	-3.2
Energy intensive manufacturing	-3.2	-7.0	-6.9	0.4	-3.8	-8.9	-39.6	-19.1	-26.0	-11.7	-23.5	-20.9	-21.1	-14.6	-12.3	-4.3	-23.6	-12.5
Other manufacturing	-7.1	-2.3	-3.7	-0.5	-0.2	1.4	3.5	2.9	12.2	1.5	1.4	5.9	1.4	4.5	4.6	-3.1	3.0	0.0
Other industries	-5.9	-2.8	-2.3	-14.5	-3.3	2.1	4.2	1.4	7.1	0.6	1.7	0.8	2.6	6.5	7.3	-7.5	3.5	-1.0
Service	-4.6	-3.3	-0.2	-2.1	1.2	4.4	6.0	2.7	16.2	6.5	4.8	10.5	3.8	6.4	10.2	-2.9	5.7	0.4
Total	-5.8	-4.3	-4.1	-2.7	-0.5	-1.4	-2.4	-1.4	-3.7	-0.7	-0.8	-2.2	-1.3	-1.2	-2.0	-3.9	-1.8	-2.9
BTADR																		
Agriculture	-5.9	-2.8	-3.2	-0.7	-1.5	-1.5	-0.4	1.2	7.3	-1.2	-1.5	1.0	-1.2	2.4	1.5	-2.8	-0.3	-2.2
All energy	-9.8	-20.8	-3.8	-7.7	8.7	-1.6	0.2	6.5	-5.2	-3.5	-3.9	-2.0	-9.7	-3.0	-7.7	-11.0	-4.7	-6.2
All manufacturing	-3.3	-3.4	-2.6	-1.6	-1.0	-1.8	-1.5	-1.3	2.0	-0.7	-1.0	-1.5	-1.8	-0.1	0.3	-2.6	-1.2	-1.9
Energy intensive manufacturing	-3.9	-10.6	-6.0	-6.7	-2.2	-7.6	-7.7	-3.2	-0.2	-2.9	-3.0	-3.2	-4.0	-1.9	-6.6	-6.1	-4.8	-5.5
Other manufacturing	-3.1	-0.5	-1.6	1.9	-0.7	0.7	-0.4	-0.6	4.9	-0.1	-0.7	-0.2	-1.2	1.2	3.2	-1.2	-0.1	-0.7
Other industries	-2.8	-1.6	-1.3	-12.4	-2.4	2.5	1.2	1.5	3.5	0.8	0.6	0.3	1.3	3.9	6.2	-5.2	2.4	-0.7
Service	-2.8	-2.5	0.2	-0.8	0.8	3.7	2.9	0.1	10.4	4.7	3.3	5.0	1.8	4.0	9.1	-1.8	3.3	0.1
Total	-3.5	-3.8	-2.3	-2.8	-0.6	-1.2	-1.2	-0.6	-1.7	-0.5	-0.6	-0.7	-0.7	-0.5	-1.6	-2.8	-1.0	-1.9

*Notes: **NBTA17:** Industrial countries alone reduce emissions by 17% and take no trade policy action; **BTAFU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in imports; **BTADU:** Industrial countries alone reduce emissions by 17% and impose tariffs on all merchandise imports based on carbon content in domestic production; **BTADE:** Industrial countries alone reduce emissions by 17% with import tariffs on all merchandise imports and rebates on all merchandise exports based on carbon content in domestic production; **BTAFR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in imports; **BTADR:** Industrial countries alone reduce emissions by 17% and impose tariffs on energy-intensive merchandise imports based on carbon content in domestic production*

Appendix Table 7. Share of Output by sector (% of total output, 2004)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC
Agriculture	1.7	1.2	1.1	2.1	1.3	6.2	6.2	13.2	4.3	5.2	14.8	8.9	5.9	8.9	5.3
All energy	3.1	4.0	2.7	5.8	5.2	8.3	7.1	9.8	24.1	9.5	7.7	22.2	23.4	10.6	9.3
All manufacturing	35.3	23.9	31.8	25.9	42.2	33.9	49.8	35.4	23.8	47.5	31.5	24.4	24.3	29.3	41.3
Energy intensive manufacturing	11.1	7.2	10.0	9.2	13.0	11.5	15.7	10.9	10.7	10.7	4.7	8.9	7.4	9.8	12.6
Other manufacturing	24.3	16.8	21.8	16.7	29.1	22.3	34.1	24.5	13.1	36.8	26.8	15.5	16.9	19.5	28.7
Other industries	5.9	7.0	7.5	8.8	6.5	8.9	10.9	8.5	8.5	7.1	8.4	9.0	7.7	7.5	5.4
Service	53.9	63.9	56.9	57.3	44.9	42.8	26.0	33.1	39.3	30.7	37.6	35.5	38.7	43.6	38.7
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Appendix Table 8. Share of Exports by sector (% of total exports, 2005)

	EU27 with EFTA	United States	Japan	Rest of high income Annex 1	Rest of high income	Brazil	China	India	Russia	Rest of East Asia	Rest of South Asia	Rest of ECA	Middle East and North Africa	Sub-Saharan Africa	Rest of LAC
Agriculture	0.8	3.7	0.1	4.1	0.1	10.4	1.1	3.7	0.6	1.7	3.4	4.3	1.9	7.9	6.2
All energy	2.5	2.2	0.3	10.0	2.3	4.3	2.0	3.6	52.9	7.1	9.7	24.7	49.4	34.6	17.8
All manufacturing	69.4	69.5	90.3	66.6	77.3	68.5	89.9	69.7	36.0	79.6	70.5	53.0	32.6	37.7	61.4
Energy intensive manufacturing	20.6	19.0	17.5	21.6	16.9	20.6	12.0	19.3	25.4	14.0	4.6	25.7	11.4	17.4	15.0
Other manufacturing	48.8	50.5	72.8	45.1	60.5	47.8	78.0	50.4	10.5	65.6	65.9	27.2	21.2	20.3	46.4
Other industries	1.8	0.9	1.1	3.6	0.2	7.2	0.6	5.0	3.4	1.6	0.7	2.8	1.8	7.4	3.1
Service	25.5	23.8	8.3	15.6	20.0	9.6	6.4	18.0	7.2	10.1	15.8	15.2	14.3	12.5	11.6
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0