Border Tax Adjustments in the Climate Policy Context: CO2 versus Broad-based GHG Emission Targeting[1]

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Abstract

Using a multi-region, multi-sector computable general equilibrium (CGE) model, this paper compares the efficiency, distributional and emission leakage effects of border tax adjustments (BTAs) as part of unilateral climate policies that are based on carbon dioxide (CO2)-only versus those based on all greenhouse gases (GHGs). Simulation results suggest that the broad-based GHG policies in general have lower efficiency costs and result in less re-distributive effects. BTAs bring modest efficiency gains with adverse distributional consequences. The distributional impacts are smaller under broad-based GHG policies compared to that based on CO2 only. However, these are due to a wider variety of abatement options under multi-gas policies rather than the BTAs per se. The main difference between the two policies is distributional effects. First, CO2-only based policies have worse impacts on fossil fuel exporters such as Russia and relatively better outcomes for oil importers such as India and China among the non-abating countries compared to that of multi-gas policies particularly when it involves large global emissions reduction. Second, sectoral coverage under BTAs also influences the differential outcomes. For example, Brazil is worse impacted under GHG-based policies if agriculture is brought under BTAs as most of its emissions are non-CO2 based and agriculture is the primary source of these emissions.

Key words: Carbon leakage, border tax adjustments (BTAs), competitiveness.
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1. Introduction

Border tax adjustments (BTAs), also termed as border carbon adjustments (BCAs), are proposed to minimize the competitiveness and emission leakage effects of unilateral greenhouse gas (GHG) reduction policies. The Waxman-Markey Bill (US Congress 2009) called for BTA in the format of emission charges to be applied on energy-intensive imports from countries that do not have economy-wide GHG reduction programs at least as stringent as those proposed in the US. Similarly, the directives of the European Parliament and of the Council (CEC 2008) also proposed border tax adjustments in the energy intensive industries which are determined to be exposed to significant risk of carbon leakage.

Although the European Union emission trading system (ETS) currently only provides free allowances to the energy-intensive industries (which is essentially a partial form of a BTA), the newly-appointed French minister for "industrial revival", Arnaud Montebourg, recently declared that he would revive a plan for a carbon tariff at the EU's borders on imports from countries not undertaking comparable efforts in reducing GHG emissions.[2] Literature on this topic covers a wide-range of areas: compatibility of BTAs with WTO rules; competitiveness; emission leakage; and the effectiveness of BTAs in addressing these concerns.[3] However, numerical works on the implications of BTAs using a computable general equilibrium (CGE) framework have focused essentially on CO2 emissions only. These ignore the role that other GHGs might play in determining overall carbon prices, tariff base and rates at the border and the efficiency and distributional consequences at the regional and global level. Other greenhouse gases (i.e., methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF6), etc.), henceforth referred to as non-CO2 gases, constitute a sizable fraction (about a quarter) of total global GHG emissions in CO2 equivalent terms. Different types of GHG emissions are converted into CO2 equivalents using the respective global warming potential over a 100 year time horizon. While the inclusion of all GHGs under BTAs expands the tariff base at the border, the carbon prices with fixed

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[2] Please refer to - http://www.guardian.co.uk/environment/2012/may/18/france-eu-carbon-tariff

[3] See for example Lockwood and Whalley (2008), Stavins (2008), Biermann and Rainer (2005), Brewer (2008), De Cendra (2006), McCorriston and Sleldon (2005), Ismer and Neuhoff (2007) and Goh, Gavin (2004). Asselt and Biermann (2007) evaluate proposed measures on a set of political and legal criteria, including environmental effectiveness in the European context.

target are expected to be lower due to relatively cheap abatement options for several of the non-CO2 GHG sources (Blok et al. 2001, Harmelink et al. 2005) and flexibility in abatement options (Hayhoe et al. 1999, Hyman et al. 2003, Jensen and Thelle 2001, Lucas et al. 2005 and 2006, Manne and Richels 2001, Reilly et al., 1999, 2003, Tol 1999, and Van Vuuren et al. 2003). It is not clear what would be the net impacts from the two opposing forces (i.e., a larger carbon base and lower carbon prices under GHG based policies) on individual abating and non-abating countries and sectors.

Moreover, regions as well as economic sectors vary widely in terms of emission shares of non-CO2 gases. For example, two-thirds of GHG emissions in Brazil are non-CO2 related as against a global average of one quarter, and agriculture constitutes a major share of non-CO2 emissions. Therefore, altering the tax base from CO2 to all GHGs would have significant implications for these sectors and economies. The objective of this paper is to examine the differences in the efficiency, distributional and carbon leakage effects of unilateral climate policies when the border taxes are based on different measures of the GHG emissions - just CO2 emissions versus broad-based GHG emissions.

A static multi-region, multi-sector computable general equilibrium model is used to study the impacts of BTAs under three abating coalition settings – Europe, Annex 1, and Annex 1 plus China. Border tax adjustments are based on embodied carbon content of the product which is estimated by a detailed multi-regional input-output (MRIO) framework.

Simulation results suggest that the inclusion of a wide range of GHGs is favorable in all cases, as it widens the tax base and lowers the tax rate. This not only reduces the efficiency cost of emission abatements in the cases without BTAs, but also reduces the burden shifting effect when BTAs are enacted. While BTAs generate a modest welfare benefit at a global level, they are generally found to shift some of the efficiency cost of abatement policy from the abating coalition onto the rest of the world. Since sectoral and regional share of CO2 and other gases varies, BTAs based on all GHGs yield different distributional outcome compared to that based on CO2-only. Unilateral actions by a large coalition of countries based on CO2-based BTA policies affect the non-participating producers of fossil fuels such as Russia and other oil exporting countries more than policies that are based on all GHGs. Since majority of emissions in agriculture is non-

CO2 related, when it is brought under BTAs and all GHG emissions are targeted, this sector suffers significant losses in the non-abating regions. It is interesting to note that the Europe-coalition could achieve ‘inward’ or negative emission leakage in a GHG-based policy in which agriculture along with the energy intensive trade exposed (EITE) sectors are also brought under BTAs.

In the following, an overview of the literature is provided in Section 2, followed by a brief discussion of the model in Section 3. Data and calibration procedures are discussed in Section 4. Simulation scenarios and results are analysed in Section 5 and finally, Section 6 provides a summary of the main findings and concludes.

2. Background literature

While multilateral negotiations under the United Nation’s Framework Convention on Climate Change (UNFCCC) have made considerable progress in recent years, many countries have also adopted unilateral policies. However, the main concerns regarding unilateral emission abatement policies have been the loss of competitiveness in abating countries due to costly abatements and emissions leakage. Emission leakage has been the central worry in international climate change treaty and in the design of existing emission control systems (Elliot et al. 2012). The emission leakage may take place in two ways:

1) The competitiveness effect: production being lost to firms located in countries without climate policies; and
2) The energy price effect: climate policies in participating countries reduce their demand for fossil fuels thus depressing global fuel prices, which in turn induces greater fuel demand in non-participating countries (OECD 2008).

Proponents have argued that BTAs may be used to prevent the loss of competitiveness and minimize the emission leakage problem by creating a price wedge favouring domestic over foreign goods (Markusen 1975, Hoel 1996, Gros 2009). Full border tax adjustments consist of two components – rebates in the amount of emission taxes paid by producers of exports and a tariff based on the embodied carbon content of the imported goods. These measures are consistent with the WTO’s destination principle of taxation (GATT Working Party on Border Tax Adjustments, 1970, para. 4, cited from Biermann and Brohm 2005). The WTO Committee on Trade and Environment endorsed this principle in the carbon tax context (WTO CTE, 1997, para 28) and it still remains as the basic view of the WTO on this issue. It should, however, be mentioned that BTAs in the

WTO are not motivated by environmental considerations, but to preserve competitive equality in international trade (Demaret and Stewardson 1994).[4]

The tariff base also depends on the coverage of direct and indirect emissions contained within a product. Direct emissions are those resulting from combustions of fossil fuels and production processes and, indirect emissions are those generated in the production of inputs used as intermediates in the production of a particular commodity. Most literature considered direct emissions only. For example, Mattoo et al (2009) consider direct emission content of the domestic and foreign product alternatively as the tariff base and find that BTAs based on the carbon footprint of foreign products would whack the developing countries as their exports would become markedly less competitive. Winchester (2011) calculates embodied emissions as CO2 emissions from direct fossil fuel use, plus CO2 emissions from electricity production used by that sector. However, Rutherford and Babiker (1997) calculate embodied emissions as the sum of both direct and indirect emissions. In this paper a fully embodied carbon accounting rule based on the MRIO framework is applied for border tax purposes (Peters et al 2011, Ghosh and Siddiqui 2011).

There is a wide body of literature on the effectiveness of BTAs in offsetting the competitiveness and emission leakage effect. Numerical modeling works on the effects of border measures have focused on single or multiple countries. In these studies, different models are used with a variety of targets to be achieved, for example, the achievement of Kyoto targets (Babiker and Rutherford 2005, Peterson Schleich 2007) or a long-term target for 2050 (Winchester et al. 2010) and the imposition of a particular carbon tax (McKibben and Wilcoxen 2009, Dissou and Eyland 2009, Fischer and Fox 2009). In general, literature suggests that BTAs reduce the negative competitiveness impacts of climate policies on the energy-intensive and highly traded sectors and mitigates the leakage effect. However, the findings on welfare effects are mixed.

Studies that used small open-economy (SOE) CGE models suggest that BTAs reduce the competitiveness effects in some carbon intensive industries but the overall economy

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[4] Further discussions on the compatibility of BTAs for climate policies with the WTO can be found in Biermann and Brohm (2005), Frankel (2008), Brewer (1998) and Goh (2004).

suffers economic loss (for example, Rivers (2010), Bataille et al (2009), and Dissou and Eyland (2011) on Canada). These findings seem obvious as in an SOE formulation, as, by definition no international spillover effects (i.e., neither terms-of-trade (ToT) nor leakage effects) are properly addressed.

In the multi-country context, literature suggests that the marginal contribution of BTAs on global welfare is small but has significant distributional consequences. Winchester *et al*. (2010) find modest gains to energy-intensive manufacturing sectors from BTAs, with small or nonexistent welfare impacts in the US. McKibbin and Wilcoxen (2009) find that the border adjustments or "green tariffs" on imports from countries with little or no climate policy would be small in the US context. It would have only modest impact on the reduction of carbon leakage and do very little to protect import-competing industries. OECD (2008) finds that leakage effects would depend on the size of the group of countries that constrain emissions. The importance of leakage diminishes as this group grows. Kuik and Hofkes (2010) find that reduction of the overall or macro rate of leakage would be modest if the EU imposes BTAs. So, from an environmental point of view border tax adjustments would not be a very effective policy measure, but might be justified by considerations of sectoral competitiveness. Böhringer et al. (2012) find that embodied carbon tariffs do effectively reduce carbon leakage.[5] However, the scope for improvements in the global cost-effectiveness of unilateral climate policy is limited. The main welfare effect of the tariffs is to shift the burden of OECD climate policy to the developing world.

3. The static multi-sector, multi-region CGE model

In this paper a version of Environment Canada's static multi-sector, multi-region (EC-MS-MR) computable general equilibrium is used. This is a modified version of the model used in Böhringer and Rutherford (2010). The modification has essentially been made to include the non-CO2 abatement options in the model. Algebraically, the model is formulated as a mixed complementarity problem (MCP) and numerically implemented in MPSGE (Rutherford 1999) as a subsystem of GAMS (Brooke et al. 1996) using PATH

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[5] Goulder and Hafstead (2011), Fischer and Fox (2009) and Winchester (2011) also explore effectiveness of alternative leakage prevention policies. Winchester finds that the leakage can be eliminated by modest non-Coalition measures, such as cap-and-trade within the coalition.

(Dirkse and Ferris 1995). A summary of the algebraic formulation of the model is provided in Appendix 1. In the following, a non-technical description along with detailed discussions on the non-CO2 abatement options of the model is provided.

In order to capture the heterogeneity across regions in the global economy in terms of income, energy and emission intensity and the composition of GHGs the model is disaggregated into 12 regions. These include United States, China, India, Russia, Brazil, EU 27 plus EFTA, rest of Annex 1 countries, energy exporting countries, middle income countries and low income countries (Appendix 2). Similarly, in order to analyze the differential impacts of unilateral carbon policies at the sector level, the model is disaggregated into 14 output producing sectors based on emission intensity and its composition (i.e., CO2 and other) and trade orientation (Appendix 3). This includes three primary fossil fuel sectors (coal, crude oil, and natural gas), five energy intensive trade exposed (EITE) sectors (i.e., chemicals, iron and steel, non-ferrous metals, non-metallic minerals, refined oil products) and six other sectors (agriculture, electricity and heat, pulp, paper and print, commercial and public services, transport, and all other goods).

The model distinguishes five primary factors: capital and labour that are mobile across sectors but immobile across regions; the other three are resource-specific factors, each used in one of the three primary fossil fuel sectors. The supply of each factor is fixed. Given the prices of goods, services and factors, firms in each sector choose inputs to maximize profits. Production technologies in each sector can be described by multi-level nests consisting of constant elasticity of substitution (CES) or Leontief functions (Figure 1). Differential treatment of the nesting structures are implemented in fossil fuel producing and other sectors reflecting upon their production techniques and factor/input substitution possibilities.

As shown in Figure 1, at the top level, the process related non-CO2 emissions are combined with a composite of all other inputs as a Leontief function. The composite other input in the non-fossil fuel sectors is in turn a CES function of non-energy material composite (M) and a CES aggregate of energy, capital and labour (KL-E). At the third level, a CES function describes the trade-offs between composites of value added (KL) and energy aggregate (E). At the fourth level, the substitution possibilities within value added (K-L) are implemented as a CES function of labour (L) and capital (K). Similarly, substitution possibilities within the energy bundle are captured by a CES function of electricity and other energy composite (CGO). Finally at the fifth level, composite other energy (CGO) is defined as a CES aggregate of coal (C), oil (O) and gas (G). While the top nest in fossil-fuel production is the same as in non-fossil fuel production, the remaining structure is different and simplified. At the second level (not shown here due to space constraint), a CES function combines a sector-specific fossil-fuel resource (RES) with a composite material input, labour and capital. The composite material input is a Leontief function of all intermediate inputs including coal, oil and gas.

Treatment of CO2 and non- CO2 emissions

CO2 emissions in the model are related to the combustion of fossil fuels (i.e., coal, oil, and gas) and are linked in fixed proportions to fossil fuel use in production and consumption activities. All fossil-fuel related GHG emissions can only be abated by substituting away from the fuels, and or scale reduction of activities, whereas production related emissions of non-CO2 GHGs can be abated using special abatement technologies.

Non-CO2 emissions in the model are grouped into three categories: Methane (CH4), Nitrous oxide (N2O) and fluorinated gases (FGAS) such as HFCs, PFCs and SF6. Non-CO2 emissions are mostly process related (from the uses of factors, non-energy intermediates and the production of output). A small share of non-CO2 emissions is energy related and is represented in fixed proportions to fossil fuel use. The process related emissions are incorporated in fixed proportions to output.[6]

Modeling the abatement of non-CO2 process related emissions is complicated as there are spillover effects from the control of one gas onto emissions of others (Hyman et al 2003). For example, some methods aimed at CO2 reductions (e.g., measures for efficiency improvements for large fuel combustors or automobiles) may also result in reductions in methane and nitrous oxide. There is a wide range of emission reduction technologies available for the non-CO2 GHGs including gas capture and its re-use, energy efficiency improvements, end-of-pipe controls (e.g., incineration) and leak

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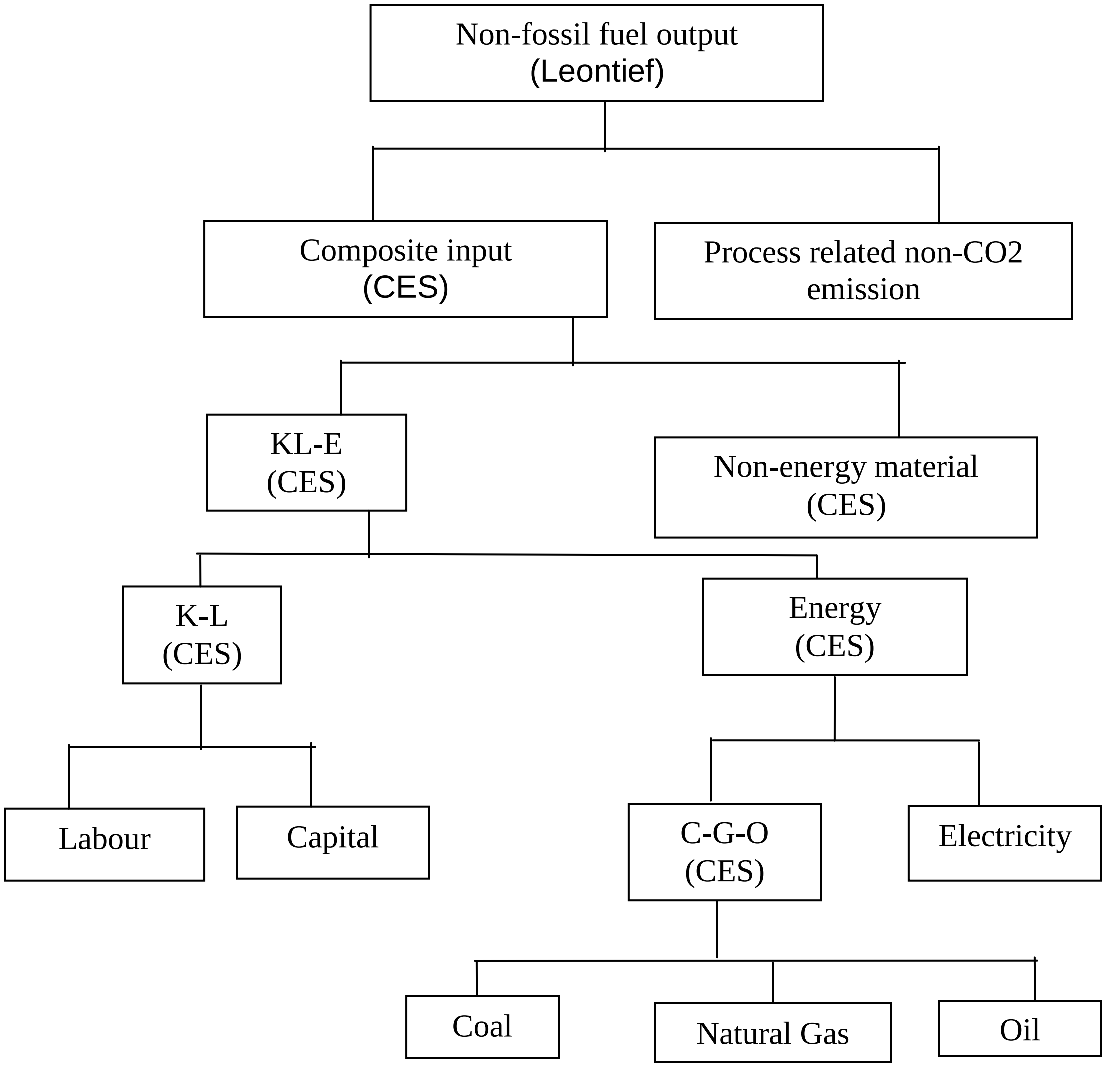
[6] Process related emissions from factor and non-energy input use constitute a very small share in total emissions.

Figure 1: Non-fossil fuel production (Y)



reduction. In this paper these complexities are handled by a simple procedure in which estimates of abatement potentials of non-CO2 emissions at various technological costs are directly integrated into the model by an activity analysis approach (Figure 2) which is similar to that described in Böhringer and Rutherford (2008). The mixed-complementarity framework used in this paper permits direct integration of all abatement activities each of which becomes effective at different carbon prices and or process oriented capacity constraints. EPA (2006) provides country specific bottom-up estimates of percentage abatements by gas across different activities (e.g., rice cultivation, enteric fermentation and manure management) by source and sector at different carbon prices.

Table 1: Sources of non-CO2 emission by sectors

Non-CO2 GHGs	Non-CO2 GHGs Source	Sector in the Model
CH4	Fugitives from natural gas and oil systems	Oil
	Fugitives from natural gas and oil systems	Crude oil
	Fugitives from natural gas and oil systems	Gas
	Fugitives from Coal Mining Activities	Coal
	Stationary and Mobile Combustion	Transportation
	Rice Cultivation	Agriculture
	Manure Management	
	Other Agricultural Sources	
	Biomass Combustion	Service
	Other Industrial Non-Agricultural Sources	
	Landfilling of Solid Waste	
	Wastewater	
	Non-Agricultural Sources (Waste and Other),	
N2O	Agricultural Soils	Agriculture
	Other Agricultural Sources	
	Manure Management	
	Stationary and Mobile Combustion	Transportation
	Adipic Acid and Nitric Acid Production	Chemical industry
	Human Sewage	Service
	Biomass Combustion	
	Other Industrial Non-Agricultural Sources	
	Non-Agricultural Sources (Waste and Other)	
FGAS	HFC and PFC Emissions from ODS Substitutes - Refrigeration Air Conditioning	All other goods
	HFC, PFC, SF6 Emissions from Semiconductor Manufacturing	
	PFC Emissions from Primary Aluminum Production	Non-ferrous metals
	SF6 Emissions from Magnesium Manufacturing	
	HFC and PFC Emissions from ODS Substitutes - Aerosols	Chemical industry
	HFC and PFC Emissions from ODS Substitutes - Fire Extinguishing	
	HFC and PFC Emissions from ODS Substitutes - Foams	
	HFC and PFC Emissions from ODS Substitutes - Solvents	
	HFC-23 Emissions from HCFC-22 Production	
	SF6 Emissions from Electric Power Systems	Electricity

Source: US EPA (2006).

Table 1 provides the mapping of EPA's non-CO2 emissions by gas and sources to the sectors covered in the model. The abatement estimates are only available for 5 breakeven prices of \$0, \$15, \$30, \$45 and \$60 per tonne of CO2 equivalent.[7] These estimates are available for various years including projections for years to come. In this paper the estimated abatement potentials for various non-CO2 gases for the year 2010 are used as

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[7] To avoid free-lunch issues it is assumed that no abatement takes place when the breakeven price is \$0.

no estimates for 2004 are available. As an example, percentage abatements of methane (CH4) aggregated by sectors of the model in the US is presented in Figure 3. Reflecting

Figure 2: Process related non-CO2 abatement

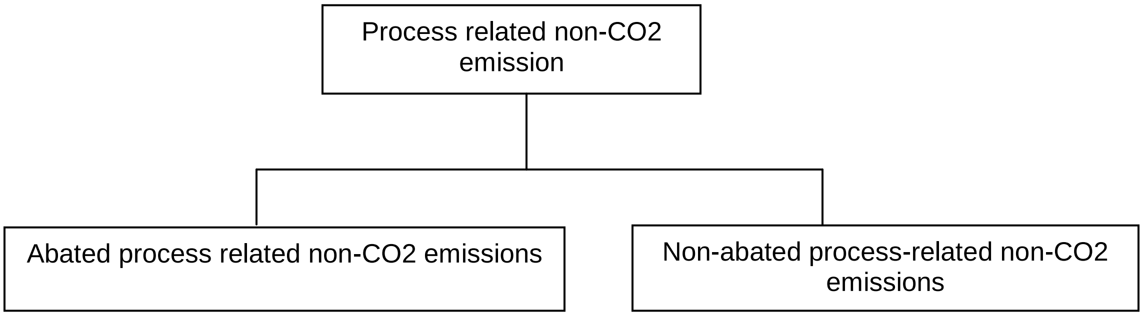
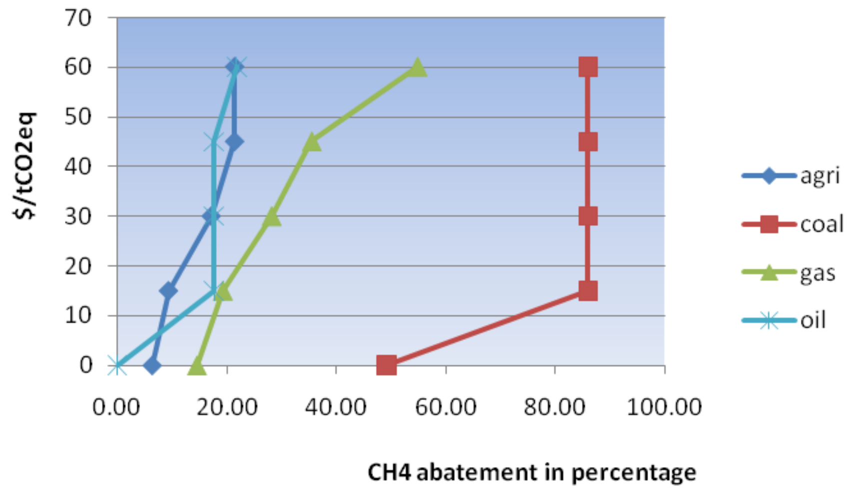


Figure 3 The US MACs for CH4 in 2010



the available technology options and its applicability the percentage abatement of the same gas varies by sectors and regions of the model. One limitation of this approach is that when carbon prices are higher than $60 per tonne (in CO2 equivalent) no additional abatements can be accounted for. Although this could be a source of potential bias in general, this is not applicable in this study as the carbon prices under GHG-based policies are lower than $60/tonne of CO2 equivalent. The process related emissions from the three categories are distinctly modeled. Depending upon the carbon price, firms decide the level of abatements to undertake by choosing the best available technology (and bear the associated costs) and pay the carbon price for the remaining emissions.[8] Emissions constraint in the model is met by an endogenous tax or emission price under a cap-and-trade system within the region undertaking abatement actions. Firms undertake abatement activities in process related non-CO2 emissions only under GHG-based policies. However, a small amount of non-CO2 emission abatement takes place even under a CO2-only policy from fuel switching and changes in activity levels. Abatement under CO2-only policy operates through change in sectoral activities and fuel mixes. Revenues from emission taxes or sales of carbon permit are recycled lump-sum to the representative agent in the respective region.

Households

Each region is represented by a single household who owns all primary factors including resources; receives factor incomes, rents, transfers from government; and pays taxes on factor income and goods and services. The representative household chooses bundles of goods and services to maximize utility subject to a budget constraint with exogenously specified investment and government provision of goods and services. Preferences across commodities are represented again by nested CES functions taking appropriate substitution possibilities in consumption across goods and services.

Regions are linked through international trade. Following the Armington (1969) approach in each region domestically produced goods are differentiated from imported goods. This treatment helps to accommodate the cross hauling in trade data. Total supply of a good to the domestic economy is formed by a CES aggregator of the domestically produced good and the composite imported good of the same kind. The composite imported good in turn is a CES aggregate of the goods imported from different origin. Goods for exports are the same domestic variety used for forming Armington goods. It is also assumed that each region maintains a constant current account balance.

The model specifies several fiscal instruments based on available data in the GTAP data base. As such it includes policy instruments such as taxes/subsidies on labour, capital,

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[8] Hyman et al (2003) modeled process related non-CO2 emissions as inputs to a CES production function. The elasticity of input substitutions in the respective nest of the production function is estimated to match the EPA’s abatement potential estimates.

resource factor, output, intermediate and final consumption. The inclusion of existing distortions is important for policy analysis for capturing the complex tax interaction effects introduced by the policies (Fisher and Fox 2010 and Goulder and Hafstead 2011).

4. Data and parameterization of the model

The main source of data used in the model is the GTAP 7.1 (Global Trade Analysis Project) database which provides detailed accounts of regional production, consumption, bilateral trade flows, energy flows, and CO2 and non-CO2 emissions, for the base year 2004 (Narayanan and Walmsley, 2008).[9] As is customary in applied general equilibrium analysis, base year data together with exogenous values of elasticity is used to determine the free parameters of in the model (Mansur and Whalley 1984, Böhringer, Löschel and Rutherford, 2007). The model is calibrated with initial taxes (subsidies) and tariffs as described above. These include those imposed on output, factor (labour, capital and resources) and intermediate inputs and final consumption. Values of elasticity that determine the responsiveness in demand and supply to changes in prices induced by policy shifts play a central role in the quantitative impact assessment of policy reforms. The values of cross-price elasticity in substitution between labour, capital, energy and material in production are taken from Okagawa & Ban (2008). Values for trade elasticity are taken from GTAP 7.1.

As of 2004, CO2 constituted roughly 3/4th of total anthropogenic greenhouse gas emissions in CO2 equivalents at the global level (Table 2).[10] The remaining are non-CO2 GHG emissions. The CO2 emissions are from the combustion of fossil fuels namely, coal (27%), gas (18%) and oil (29%). Methane (CH4) accounts for 2/3rd of all non-CO2 emissions – the remaining being nitrous oxide and fluorinated gases (Figure 4). Agriculture accounts for more than half of global non-CO2 emissions. The primary source of non-CO2 emissions in agriculture is CH4. Livestock, manure decomposition, and rice cultivation are the major sources of CH4 emissions in agriculture. The sources of other gases are reported in Table 2.

Composition of emission by gases varies across countries (Table 2). Emissions from coal constitute a little over quarter of global GHG emissions in 2004. Coal accounts for 58 and

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[9] The latest multi-country micro-consistent economic data available is for 2004.

[10] This is our estimate based on GTAP Database version 7.1.

Table 2

CO2 and GHG emissions in 2004 (million metric tonnes (MMt) and % of GHGs)

	Total GHG	CO2 by fuel type as % of GHG				Non-CO2 as % of GHG			
	MMt	Total	Coal	Gas	Oil	Total	CH4	FGAS	N2O
Brazil	825	36.1	2.5	5.3	28.3	63.9	38.9	1.0	23.9
China	5847	73.6	57.6	0.1	15.9	26.4	13.5	1.5	11.3
Rest of energy exporting countries	3538	70.1	4.0	32.2	33.9	29.9	23.7	0.4	5.8
EU 27 + EFTA	5033	81.0	20.8	23.0	37.1	19.0	9.0	1.7	8.3
India	1636	64.9	42.5	3.9	18.5	35.1	30.4	0.6	4.1
Japan	1175	91.9	21.3	15.8	54.7	8.1	1.7	3.9	2.5
Low income countries	1862	35.6	7.4	15.1	13.1	64.4	42.9	0.3	21.2
Middle income countries	3853	69.2	22.2	15.1	31.8	30.8	19.9	1.5	9.5
Rest of annex 1 countries	2215	67.1	19.3	23.1	24.7	32.9	23.9	1.2	7.9
Russia	1930	79.9	16.1	45.3	18.5	20.1	15.6	1.4	3.1
United States	7152	84.9	28.4	22.2	34.3	15.1	7.5	2.2	5.4
TOTAL	35063	73.4	26.5	18.3	28.5	26.6	16.7	1.5	8.5

Source: Computed from GTAP 7.1 and GTAP 7 Satellite data and Utilities for non-CO2 emissions.

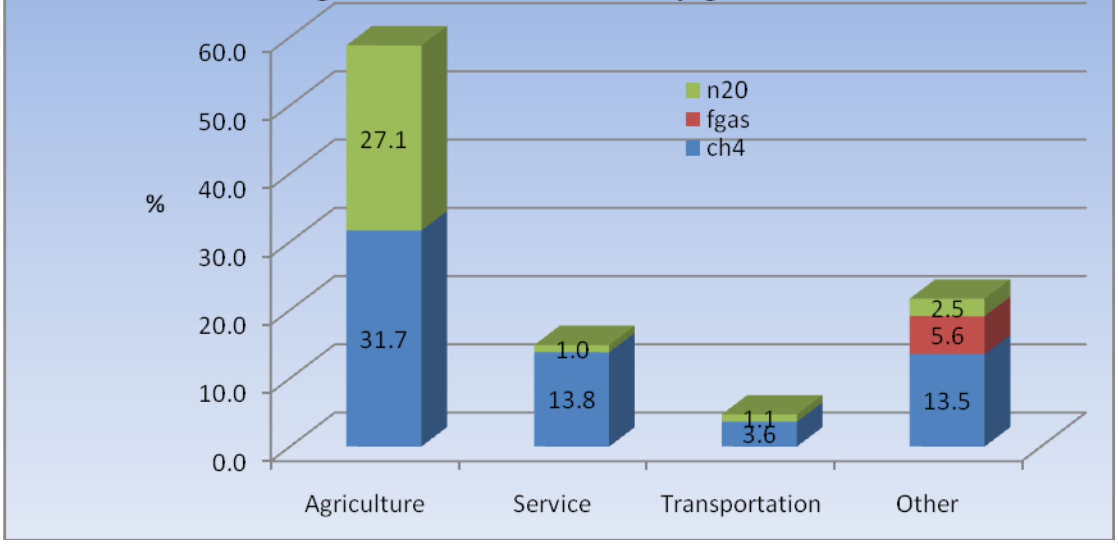
Figure 4: Non-CO2 GHGs by gas and sector

Source: GTAP 7.1 database

43 percent of total emissions in China and India. Coal combustion is the second largest source of GHG emissions in US (28 percent) after oil (34 percent). Brazil and other low income countries (LIC) have the highest shares (64%) of non-CO2 emissions in their total GHG emissions. The large majority of Brazil's GHG emissions come from burning linked to deforestation of the Amazon biome, and not from fossil fuels (Cerri et al. 2007). Hydro are the main source of electricity and the majority of liquid fuel for transport comes from sugar cane which greatly reduces CO2 emissions from fossil fuel combustions in Brazil.

5. Simulation scenarios and results

Border tax adjustments are based on the embodied carbon content of the exported and imported goods. Following Böhringer et al. (2012), in this paper a detailed multi-regional input-output (MRIO) accounting framework is used for estimating embodied carbon within a product. In this approach, both direct emissions in the production process as well as all the emissions that occurred in providing inputs of goods and services (irrespective of the regional sources) are estimated. For a review of this approach, please see Wiedmann (2009). For CO2-based policies, embodied carbon calculation is based on CO2 emission only, while for multi-gas policies emissions from all GHG sources are accounted for. The estimation of embodied carbon is based on the base year’s data and these estimates are used for BTAs purposes. Table 3 provides estimates of embodied carbon content of energy intensive commodities by region. The addition of non-CO2 emissions in carbon accounting has varied impacts at the sector and regional levels. For example, in case of Brazil, the carbon content in agriculture is estimated to be 20 times that of CO2 emissions if all GHGs are included. In general, estimated carbon content in agriculture for all regions increases by a factor of 2 to 10 of that of CO2 emissions. For other commodities, the inclusion of all GHGs in embodied carbon accounting has relatively smaller impacts.

Sectoral coverage is another important issue for BTAs. Ideally, for economic efficiency considerations broad sectoral coverage should be pursued. However, policy proposals in the EU and the US have considered BTAs targeting the energy intensive trade exposed (EITE) sectors. These include five sectors in the model - chemicals, iron and steel industry, non-ferrous metals, non-metallic minerals, refined oil products. However, emission data reveal that agriculture is the primary source of non-CO2 emissions. Given the focus of the study, it would be interesting to examine how agriculture is impacted under the two policy regimes in the abating and non-abating countries. Two sectoral coverage scenarios are therefore considered. In the first, BTAs are introduced in the five EITE sectors and in the second agriculture is included along with these sectors.

Selection of region or coalition of regions undertaking unilateral climate actions

The impact of BTAs is expected to depend on the size of tariffs (essentially determined by marginal costs of abatements within coalition regions, the targeted reduction and the carbon content of imports) and the ability of the country/region to affect the term-of-trade. Intuitively, the bigger the region undertaking abatements, the higher will be the aggregate reductions, and the lower would be the emission leakage. The overall impacts will therefore depend on the size and composition of the coalition as well. To address these issues the following three hypothetical set of coalitions are formed, which act one at a time to unilaterally reduce global emissions by specified targets based on its emissions.

1. Europe (EU 27 + EFTA)
2. Annex1 countries (excluding Russia) [11]
3. Annex1 plus China (excluding Russia)

The inclusion of China within an abating coalition is to assess the impacts of a low cost abating country on welfare and income distribution. These three coalitions account for 4.7%, 44.4% and 61.1% of global GHG emissions respectively in 2004.[12]

Simulation scenarios

It is assumed that each coalition undertakes a net reduction at the global level by an amount equivalent to 20% of the coalition's benchmark GHG emissions in 2004. Setting the net reduction target at the global level implies that any emission leakage would have direct bearing on the coalition's effective reduction. This implies that if emissions in rest

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[11] Annex 1 includes 41 industrialized countries and economies in transition. The European Union is also a member of Annex 1. The European Free Trade Association (EFTA) is an intergovernmental organization set up for the promotion of free trade and economic integration to the benefit of its four member States. These include Iceland, Liechtenstein, Norway and Switzerland.

[12] The respective shares of CO2 emissions of these regions are 15.8%, 49.4% and 66.1% of global CO2 emissions in 2004.

of the region (i.e., within non-coalition) increase (decline) due to policy actions taken in abating countries the required reductions by the coalition also increase (decrease). The

Table 3
CO2 and GHG emission content based on MRIO approach in 2004
(tonne of CO2e /$1000)

	Chemicals	Iron and Steel	Non-ferrous metals	Non-metallic minerals	Petroleum and coal products	Agriculture
CO2 emissions only						
Brazil	0.88	2.00	1.62	1.43	0.60	0.63
China	3.09	3.94	3.16	5.36	2.21	1.49
Other energy exporting countries	3.10	4.07	2.62	3.07	2.65	0.64
EU 27 plus EFTA	0.51	1.11	0.95	0.86	0.47	0.41
India	2.48	3.96	4.49	5.87	0.47	1.07
Japan	0.62	1.00	0.79	0.70	0.41	0.50
Low income countries	3.77	5.62	2.87	4.68	1.11	0.55
Middle income countries	1.22	2.22	1.16	2.23	0.69	0.59
Rest of annex 1 countries	1.17	2.41	2.11	1.78	1.16	0.65
Russia	5.25	4.85	4.48	4.82	1.93	1.44
United States	0.97	1.45	1.52	1.50	1.19	0.57
Multi-gas GHG emissions (all inclusive)						
Brazil	1.49	2.40	2.46	1.66	0.88	10.82
China	3.92	4.34	3.67	5.82	2.66	6.21
Other energy exporting countries	3.52	4.39	3.12	3.35	3.59	3.94
EU 27 plus EFTA	0.71	1.22	1.24	0.95	0.61	1.87
India	3.04	4.31	5.00	6.27	0.83	3.82
Japan	0.78	1.07	0.93	0.76	0.57	0.94
Low income countries	4.75	6.76	3.86	5.84	2.77	7.17
Middle income countries	1.54	2.42	1.41	2.45	1.06	3.59
Rest of annex 1 countries	1.46	2.69	2.72	2.01	1.69	3.40
Russia	6.09	5.34	5.47	5.27	3.63	4.29
United States	1.19	1.58	1.80	1.61	1.47	2.73

Note: These estimates are based on multi-regional input-output (MRIO) framework as elaborated in Böhringer et al (2012).

coalition achieves the required reduction under two policy options - CO2-only and broad-based GHG policies. For each coalition, six simulations with the same reduction target are performed as follows:

a) CO2-REF (Reference CO2 case): Imposition of domestic taxes on CO2 emissions that are determined endogenously to meet emission reduction target.
b) CO2-EITE-Btax: (a) plus border tax measures imposed on EITE sectors.
c) CO2-EITE-Agri-Btax: (a) plus border tax measures imposed on EITE and agriculture.
d) GHG-REF (Reference GHG case): Imposition of domestic taxes on all GHG emissions that are determined endogenously to meet emission reduction target.
e) GHG-EITE-Btax: (d) plus border tax measures imposed on EITE sectors.
f) GHG-EITE-Agri-Btax: (d) plus border tax measures imposed on EITE and agriculture.

Rebates are calculated as the embodied carbon content of domestic good multiplied by the carbon price while the border tariffs are estimated as the embodied carbon content of the imported goods times the carbon price. The reference cases for CO2-only and multi-gas policies will help to understand how flexibility matters in carbon policies in general. These along with results from other simulations will be used to understand the net effects of BTAs under the two policy regimes. In the following, results from each simulation are analyzed at the aggregate level, while detail sector level analyses are undertaken for the coalition of Europe only due to space constraint.

Simulation Results

Reference case: CO2 versus broad-based GHG Policy

The impacts of policy shocks on welfare estimated as Hicksian equivalent variation (HEV) in terms of consumption aggregated at the levels of world, the abating coalition and the non-coalition (i.e., those undertaking no policy actions) are reported in Table 4. Simulation results suggest that the welfare costs of a broad-based GHG reduction policy is almost half of those based on the CO2 emissions only. This result holds for the coalition, non-coalition and the global level. This implies that the broad-based policy for emission reductions is efficiency enhancing both for the coalition as well as the non-coalition countries. The global welfare cost falls from -0.73 percent to -0.39 percent in the reference case when Annex 1 countries choose GHG rather than CO2 based policies. Welfare cost goes down for Annex 1 countries from -0.70 to -0.36 percent and for the non-coalition from -0.84 to -0.50 percent compared to the benchmark consumption.

The main driver of this relative gain is the flexibility in abatement options – the equalization of abatement costs across various GHG gases. When comparing different coalition outcomes in the reference case, it appears that economic cost of emission abatement in Europe is the highest. Interestingly, Europe could reduce its welfare costs by 2/3rd from -1.58 percent to -0.55 percent of consumption by moving from CO2 to broad-based GHG policy. The inclusion of China into a broader coalition with Annex 1 reduces the global cost of abatement significantly. In this case the welfare loss at the world level decreases from -0.73 to -0.55 percent under CO2-based policy, and from -0.39 to -0.29 percent under GHG-based policy in the reference cases. The absolute emission reduction in this case is also higher. This relative gain is mainly driven by the lower marginal costs of abatements in China which are partially reflected by its large share (58%) of emissions from coal in China (Table 2).

Border tax adjustment

Simulation results suggest that while BTAs generate a modest welfare benefit at a global level, they are generally found to shift some of the efficiency cost of abatement policy from the abating coalition onto the rest of the world. For example, when the EU imposes

Table 4
The welfare impacts of net global GHG reduction equivalent to 20% of coalition's GHGs emissions under various policy options
(% change compared to benchmark)

	CO2-based policies			GHG-based policies		
	CO2-REF	CO2-EITE-Btax	CO2-EITE-Agri-Btax	GHG-REF	GHG-EITE-Btax	GHG-EITE-Agri Btax
Europe targets emissions reduction						
World	-0.603	-0.445	-0.438	-0.221	-0.184	-0.180
Europe	-1.579	-0.889	-0.875	-0.553	-0.309	-0.315
Non-coalition	-0.146	-0.237	-0.233	-0.065	-0.126	-0.117
Annex 1 targets emissions reduction						
World	-0.726	-0.658	-0.656	-0.385	-0.364	-0.361
Annex 1	-0.698	-0.466	-0.465	-0.357	-0.231	-0.235
Non-coalition	-0.841	-1.431	-1.424	-0.495	-0.899	-0.868
Annex 1 and China target emissions reduction						
World	-0.545	-0.533	-0.533	-0.289	-0.291	-0.293
Annex 1 + China	-0.522	-0.384	-0.384	-0.278	-0.212	-0.216
Non-coalition	-0.657	-1.268	-1.267	-0.344	-0.680	-0.677

the BTAs on EITE sectors, its welfare improves from -1.58% in the reference case to -0.89% under CO2 based policy and from -0.55% in the reference case, to -0.31% under GHG based policy. Non-coalition welfare on the other hand declines from -0.15% in the reference case to -0.24% under BTAs in the CO2 case, and from -0.07% in the reference case to -0.13% under BTAs with GHG-based policies. The global efficiency costs of abatement are further lowered although marginally if BTAs are extended beyond EITE sectors to include agriculture for the coalitions of annex1 and Europe. In contrast to other scenarios the global efficiency cost is marginally higher under BTAs in the GHG based policy case for the coalition of Annex 1 plus China. This coalition accounts for 61% and 66% of global GHG and CO2 emissions. Given its size, one can expect the leakage effects to be smaller and the terms-of-trade effects to the rest of the world to be higher. Thus, while the coalition still improves welfare relative to reference case, the losses incurred by rest of the world are bigger than the coalition's efficiency gains.

The benefits from BTAs to the coalition come from re-gaining part of the lost competitiveness, reduced leakage and positive terms-of-trade effect. In the aggregate, BTAs in general bring gains at the aggregate level relative to the reference case due to minimization of leakage and consequent equalization of marginal abatement costs of imported and domestic goods to some extent. Emission leakage decreases when GHG-based instead of CO2-only policies are pursued and further when BTAs are enacted (Table 5). For example, when the coalition of Europe pursues the CO2-only policies, emission leakage drops from 26 percent in the reference case to 13 percent under BTAs implemented in EITE sectors. If policies are based on all GHGs, the leakage drops from 12 to 1 percent when only EITE sectors are brought under BTAs. Further, if agriculture is brought under BTAs along with the EITE sectors in Europe, the net effect on leakage becomes negative (-8%). This implies that 8% of Europe's total target is met by emission reductions in the rest of the world. It is also interesting to note that with broader sectoral coverage of BTAs, the non-coalition welfare improves as well. The differential leakage effects under different policies are the reflections of emission prices and the tariffs that create the price wedge between the abating and non-abating countries. When policy in Europe is shifted from reference to BTAs targeted to EITE sectors and then to EITE and agriculture, the emission price drops from over $151 to $105 and $101 per tonne in the CO2-based policy case and from $52 to $41 and $32 per tonne in the GHG-based policy case and so are the leakage rates (Table 5).

Table 5: Emissions price and emissions leakage under alternative unilateral climate policies

	CO2-based policies			GHG-based policies		
	CO2-REF	CO2-EITE-Btax	CO2-EITE-Agri-Btax	GHG-REF	GHG-EITE-Btax	GHG-EITE-Agri-Btax
CO2 Price($/tonne CO2 eqv)						
Europe	151.26	105.34	101.75	52.35	41.15	34.61
Annex 1	81.28	70.48	69.82	37.82	33.92	31.77
Annex 1+ China	51.26	48.01	47.82	20.31	19.48	18.76
Emission Leakage as % of Coalition’s reduction						
Europe	26.25	9.49	9.44	12.29	1.14	-7.75
Annex 1	10.25	1.15	1.25	5.77	-0.32	-4.11
Annex 1+ China	5.34	0.64	0.69	2.49	-0.02	-1.95

Sectoral impacts

The analysis of the impacts at the sector level in this section is based on the simulations results from the coalition of Europe. Broadening of carbon tax base from CO2 to all GHGs would realign the sectoral abatements and burden sharing. Switching from CO2 to all GHGs negatively affects the agriculture sector as non-CO2 gases are predominant in agriculture but brings overall net gain. For example, more than half of non-CO2 gases in Europe are from agriculture. As a result, if non-CO2 gases are brought under the carbon tax, agricultural output in Europe declines by about 4% more compared to that under CO2 only reference policy (Table 6). However, the competitive position in all other sectors improves. The impacts are similar when border taxes are based on GHG emissions rather than CO2 emissions. All other sectors are better off in multi-gas compared to CO2 only policy. These results are consistent with the tariff rates imposed under BTAs (not reported here). Border tax adjustments under GHG-based policies improve the sectoral competitiveness more compared to CO2-based scenarios due to relatively higher tariffs. Inclusion of all gases allows firms to choose the cost minimizing abatement options within all GHGs. When BTAs are extended to agriculture in Europe, its competitive position in Europe turns out to be positive at 0.76 from –4.81 under GHG based policies. However, the distributional consequence on the economies relying on agricultural exports is worse (Table 7).

Table 6
Impact on sectoral output in Europe from unilateral climate policies by Europe (% change compared to benchmark)

	CO2			GHG		
	REF	MRIO-Btax	MRIO-Btax-AGR	REF	MRIO-Btax	MRIO-Btax-AGR
Agriculture	-1.36	-2.32	-0.11	-4.94	-4.81	0.76
All other goods	-0.04	-1.46	-1.56	-0.06	-0.86	-1.06
Coal transformation	-41.42	-36.28	-35.89	-32.14	-28.38	-26.05
Chemical industry	-4.64	2.41	2.27	-2.34	1.38	0.96
Crude oil	-2.65	-3.46	-3.48	-0.82	-1.64	-1.68
EITE	-7.73	0.94	0.84	-3.58	0.88	0.53
Electricity	-15.53	-10.48	-10.23	-6.97	-4.91	-4.34
Natural gas	-28.79	-23.09	-22.54	-14.77	-12.65	-10.94
Iron and steel	-10.83	1.24	1.08	-4.55	1.09	0.59
Non-ferrous metals	-16.64	9.52	9.08	-8.82	5.74	4.36
Non-metallic minerals	-5.55	-1.35	-1.40	-2.23	-0.39	-0.56
Refined oil	-13.84	-5.98	-5.80	-5.92	-2.01	-1.71
Paper-pulp-print	-1.85	-1.67	-1.69	-0.66	-0.73	-0.79
Commercial services	-0.32	-0.26	-0.28	-0.09	-0.09	-0.15
Transport	-8.25	-6.57	-6.46	-3.21	-2.92	-2.72

Distributional impacts

Results suggest that GHG-based BTAs have lower welfare and distributional effects compared to that based on CO2 only (Table 4). For example, the global welfare cost of unilateral climate policy by the coalition of Annex 1 countries by using BTAs under two coverage options based on CO2 are between -0.658 and -0.656, while those under GHG base policies are between -0.364 and -0.361 in terms of consumption. However, as discussed before the contribution of BTAs per se in GHG based policies in global welfare is small, with significant distributional consequences. The efficiency gains are essentially from the base broadening itself under the reference case. Global welfare loss in the reference case under CO2-based policy is -0.726 percent while that under the GHG-based policy it is -0.385 percent. These suggest that unilateral climate policies are more cost-effective due to flexibilities in abatement options rather than the BTAs per se.

Distributional impacts of BTAs within the non-coalition countries vary between CO2 and multi-gas policy cases and it also depends on sectoral coverage (Tables 7 and 8). In general, simulation results suggest that the non-coalition as a whole is better off under GHG based policies compared to CO2 based policies. Among the non-coalition countries, Russia and other energy exporting countries benefit the most. This is primarily driven by its impacts on carbon prices and also its indirect impacts on prices of crude oil. A lower carbon price (tax) under GHG based policies prevents dropping oil prices too much by lowering global oil demand compared to the policies that are based on CO2 only. China and India, however, suffer relative losses under GHG based policies compared to that is based on CO2-only, when the coalition of Annex1 plus China undertakes policy actions. This is partly because of the relative improvement of terms-of-trade of the fossil-fuels which constitute a major share Chinese and Indian import. By joining in a coalition with Annex1, China also bring positive welfare gains under CO2-based policies. This is essentially from selling emission permits to other coalition members and also by avoiding the border tariffs. The revenue from sales of permits to coalition members under CO2 based policy over compensates for the efficiency cost of carbon tax imposed in China due to high permit price. [13] The result that China could benefit from cooperation is also evident in other studies as well (e.g., Böhringer, Carbone and Rutherford (2012). Under the GHG-based policy case, however, the welfare effect in China is negative due to a lower carbon price.

Among the coalitions, Europe gains the most by moving from CO2 to GHG based policies. When border tax adjustments go beyond the five EITE sectors, particularly to include agriculture, distributional impacts on countries that have higher share of non-CO2 emissions are worse. For example, welfare loss in Brazil increases from -0.276 under BTAs targeted to EITE sectors to -0.463 when agriculture is included as well under the GHG policies by Annex 1 countries (Tables 7 and 8).

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[13] These results are however, based on 2004 emissions – during recent years Chinese emissions have increased dramatically. This result can be verified most recent data.

Table 7: Welfare impacts of BTAs on EITE sectors

(% change compared to benchmark consumption)

	Europe		Annex1		Annex 1 + China	
	CO2	GHG	CO2	GHG	CO2	GHG
Brazil	-0.209	-0.091	-0.479	-0.276	-0.303	-0.144
China	-0.377	-0.199	-0.999	-0.669	2.769	-0.350
Other energy exporting	-1.473	-0.848	-3.612	-2.174	-3.098	-1.590
EU 27 + EFTA	-0.889	-0.309	-0.524	-0.242	-0.483	-0.187
India	-0.176	-0.093	0.061	-0.011	0.041	-0.012
Japan	0.026	0.027	-0.811	-0.292	-0.596	-0.176
Low income countries	-0.566	-0.307	-0.664	-0.422	-0.720	-0.379
Middle income countries	-0.260	-0.122	-0.552	-0.368	-0.424	-0.267
Rest of annex 1	-0.197	-0.099	0.874	-0.439	0.139	-0.439
Russia	-3.704	-2.290	-6.500	-4.056	-5.433	-2.836
United States	-0.048	-0.018	-0.505	-0.168	-0.604	-0.200

Table 8: Welfare Impacts of BTAs on EITE and agriculture
(% change compared to benchmark consumption)

	Europe		Annex1		Annex 1 + China	
	CO2	GHG	CO2	GHG	CO2	GHG
Brazil	-0.234	-0.230	-0.509	-0.463	-0.330	-0.311
China	-0.368	-0.167	-0.995	-0.610	2.768	-0.360
Other energy exporting	-1.463	-0.783	-3.599	-2.082	-3.098	-1.556
EU 27 + EFTA	-0.875	-0.315	-0.529	-0.272	-0.487	-0.206
India	-0.176	-0.077	0.060	0.006	0.041	0.003
Japan	0.029	0.029	-0.799	-0.265	-0.591	-0.165
Low income countries	-0.607	-0.487	-0.702	-0.660	-0.753	-0.567
Middle income countries	-0.249	-0.095	-0.533	-0.305	-0.409	-0.223
Rest of annex 1	-0.199	-0.098	0.863	-0.453	0.136	-0.440
Russia	-3.670	-2.071	-6.491	-3.908	-5.445	-2.785
United States	-0.046	-0.011	-0.499	-0.156	-0.601	-0.193

6. Summary and conclusions

Border tax adjustments have been proposed in the EU and the US policy documents to address the competitiveness and the emission leakage effects of unilateral climate policies. Numerical works assessing the effectiveness of BTAs have essentially focused on CO2 emissions, ignoring the role that other GHGs might play in determining overall carbon prices, the tariff base and the rates at the border and its implications for efficiency and distribution. Using a multi-region, multi-sector CGE model this paper analyses the differences in the efficiency, distributional and carbon leakage effects of unilateral climate policies when border tax adjustments are based on different measures of the GHG emissions - just CO2 emissions versus multi-gas greenhouse gas emissions. It also examines the implications of BTAs that goes beyond the currently considered energy intensive trade exposed (EITE) sectors to include agriculture in particular, which accounts for more than half of non-CO2 emissions.

Simulation results suggest that the efficiency costs of broad-based GHG policies are much lower than those based on CO2-only with a constant emission reduction target. Emission leakages under GHG-based policies are also lower. BTAs under both CO2-based and broad-based GHG policies reduce emission leakage, reduce competiveness effects and bring significant gains to the coalition of regions undertaking unilateral climate policy actions. These gains to the coalition region under BTAs are, however, at the cost welfare in non-abating countries with modest or no improvements in global welfare and due to a wider variety of abatement options under multi-gas policies rather than the BTAs per se.

At a sector level, agriculture is impacted more compared to CO2-based policy when all GHG emissions are brought under the carbon tax/price base as it is responsible for more than half of non-CO2 GHG emissions. Although by including agriculture within BTAs, its competitive position in the coalition countries, can be improved, its impacts on the non-coalition countries relying on agricultural exports, for example, Brazil would be worst if GHG-based policies are enacted. It is also important to note that since CO2 emissions are essentially fossil fuel related, unilateral climate policies based on CO2 emissions only would have relatively worse impacts on fossil fuel exporters in the non-abating countries compared to that of multi-gas policies. Simulation results indicate that while oil exporting nations (e.g., Russia) are impacted the worst under unilateral climate policies based CO2-based emissions, the economies of China and India, (large importers of oil) are better off essentially due to depressing world prices of oil.

Finally, results presented in this paper are based on underlying modeling assumptions, the data and the values of parameters used in model calibration. The bottom-up estimates of non-CO2 abatements available at detailed sector level are aggregated to the model sectors. This may result in some potential bias in the simulated impacts. More accurate information on abatement possibilities could potentially change the magnitude of the impacts but it is expected that the direction of results to remain the same. Results in this paper should therefore be viewed as indicative of the directions of changes might take place from the carbon abatement policies studied.

References

Armington, P.S. (1969), “A Theory of Demand for Products Distinguished by Place of Production”, *International Monetary Fund Staff Papers*, Vol. 16, pp 159-76.

Asselt, Harro van & Frank Biermann (2007), “European Emissions Trading and the International Competitiveness of Energy-Intensive Industries: A Legal and Political Evaluation of Possible Supporting Measures” *Energy Policy* 35 (1): 497-507.

Atkinson G., K. Hamilton, G. Ruta and D. Van Der Mensbrugghe (2010), Trade in ‘Virtual Carbon’, Empirical Results and Implications for Policy, Policy Research Working Paper, World Bank.

Babiker, Mustafa and Thomas Rutherford (2005), “The Economic Effects of Border Measures in Subglobal Climate Agreements”, *Energy Journal* 26:4.

Bataille, Chris; Dachis, Benjamin and Rivers, Nic (2009), “Pricing Greenhouse Gas Emissions: The Impact on Canada’s Competiveness”, C.D. Howe Institute Commentary No. 280, February.

Biermann, Frank; Brohm, Rainer (2005), "Implementing the Kyoto Protocol without the USA: The Strategic Role of Energy Tax Adjustments at the Border", *Climate Policy*, 4(3): 289-302.

Blok, K., De Jager, D., Hendriks, C., (2001) "Economic Evaluation of Sectoral Emission Reduction Objectives for Climate Change—Summary Report for Policy Makers." Ecofys,Utrecht, The Netherlands.

Böhringer, Christoph and Thomas F. Rutherford (2010), "The Costs of Compliance: A CGE Assessment of Canada’s Policy Options under the Kyoto Protocol", *The World Economy*, doi: 10.1111/j.1467-9701.2009.01229.x, pp 177-211.

Böhringer, Christoph, Andreas Löschel and Thomas F. Rutherford (2007),"Efficiency Gains from "What"-Flexibility in Climate Policy: An Integrated CGE Assessment", *Energy Journal* pp 405-424..

Böhringer, Christoph and Thomas Rutherford (2008), “Combining bottom-up and top-down,” *Energy Economics*, Vol. 30, No. 2, pp. 574-596.

Böhringer, Christoph, Carolyn Fischer, and Knut Einar Rosendahl (2010), "The Global Effects of Subglobal Climate Policies", *The B.E. Journal of Economic Analysis & Policy*, Vol. 10, No. 2

Böhringer, Christoph, Jared C. Carbone, Thomas Rutherford (2012), “The Strategic Value of Embodied Carbon Tariff”, paper presented at the annual meetings of the American Economic Association, January 6, 2012, Chicago.

Brewer, T. (2008), “US Climate Policy – Trade Policy Intersections, Current Status, Prospects and Implications for Carbon Leakage” Presentation to the Climate Strategies Carbon Leakage Workshop, February 4th, Paris.

Brooke, A., D. Kendrick and A. Meeraus (1996), *GAMS: A User’s Guide* (Washington, DC: GAMS Development Corporation).

Cerri, C.E.P. et al. (2007), “Tropical agriculture and global warming: impacts and mitigation options”, *Scientia Agricola*, v.64, p.83-89, 2007.

Commission of the European Communities (2008), Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading system of the Community. Brussels, 23.1.200. COM(2008) 16 final 2008/0013 (COD).

de Cendra, Javier (2006), “Can Emissions Trading Schemes be Coupled with Border Tax Adjustments? An Analysis via-a-vis WTO Law”, *Review of European Community & International Environmental Law* 15(2):131-145.

Demaret, Paul & Raoul Stewardson (1994), “BTA Under GATT – Trade, Environment and the Future” Washington, D.C.

Dirkse, S. and M. Ferris (1995), “The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems’, Optimization Methods and Software, 5, 123–56.

Dissou, Yazid and Terry Eyland (2011), “Carbon Control Policies, Competitiveness, and Border Tax”, *Energy Economics*, 33, 3, 556–564.

Elliott, J., Foster, I., Kortum, S., Jush, K.G., Minson, T., Weisbach, D., (2012) "Unilateral Carbon Taxes, Border Tax Adjustments, and Carbon Leakage" the Law School, the university of Chicago.

EPA (2006), “Global Mitigation of Non-CO2 Greenhouse Gases”, http://www.epa.gov/nonco2/econ-inv/international.html

Fischer, Carolyn and Alan K. Fox (2009), Comparing Policies to Combat Emissions Leakage: Border Tax Adjustments versus Rebates, Discussion Paper 09-02, Resources for the Future.

Fischer, Carolyn and Alan K. Fox (2010) On the Scope for Output-Based Rebating in Climate Policy: When Revenue Recycling Isn’t Enough (or Isn’t Possible) Discussion Paper 10-69, Resources for the Future.

Frankel, Jeffrey (2008), “Global Environmental Policy and Global Trade Policy” Discussion Paper 2008-14, Cambridge, Mass.: Harvard Project on International Climate Agreements.

Ghosh, Madanmohan and Muhammad Shahid Siddiqui (2011), Embodied Emissions in International Trade: Regional Dimensions with a focus on Canada, paper presented at the meetings of the Canadian Economic Association (CEA) June 3-5, 2011, held at the University of Ottawa.

Goh, Gavin (2004), “The World Trade Organization, Kyoto and Energy Tax Adjustments at the Border” *Journal of World Trade* 38 (3):395-423.

Goulder, Lawrence H. and Marc A. C. Hafstead (2011), “Addressing International Emission Leakage”, paper presented at the annual meetings of the American Economic Association, Atlanta

Gros, D. (2009) “Global Welfare Implications of Carbon Border Taxes”, CEPS Working Document No. 315.

Grossman, G. (1980) “Border Tax Adjustments: Do They Distort Trade?” *Journal of International Economics*, 10: 117-128.

Harmelink, M.G.M., Blok, K., Ter Avest, G.H., (2005) "Evaluation of non-CO2-greenhouse gas emission reductions in The
Netherlands in the period 1990–2003" Environ. Sci. 2 (2/3),339–349.

Hayhoe, K., A. Jain, H. Pitcher, C. MacCracken, M. Gibbs, D. Wuebbles, R. Harvey, D. Kruger (1999), “Costs of Multigreenhouse Gas Reduction Targets for the USA”, *Science*, 286: 905-906.

Hoel, M. (1996), “Should a carbon tax be differentiated across sectors?” *Journal of Public Economics*, 59, 17–32.

Hotelling, H. (1932). "Edgeworth's taxation paradox and the nature of demand and supply functions". *Journal of Political Economy* 40 (5): 577–616.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin and H.D. Jacoby (2003), Modeling Non-CO2 Greenhouse Gas Abatement. *Environmental Modeling and Assessment*, **8(3)**: 175-186.

Ismer, R. and K. Neuhoff (2007), “Border Tax Adjustment: A Feasible Way to Support Stringent Emission Trading” *European Journal of Law and Economics* 24:137-164.

Jensen, J., Thelle, M.H., (2001) “What are the gains from a multigas strategy?” FEEM Working Paper No. 84.

Kuik, Onno and Marjan Hofkes (2010), “Border adjustment for European emissions trading: Competitiveness and carbon leakage.” *Energy Policy* Vol. 38, 1741–1748.

Lockwood Ben, John Whalley (2008), "Carbon Motivated Border Tax Adjustments: Old Wine in Green Bottles?" NBER Working Paper # W14025.

Lucas, P.L., Den Elzen, M.G.J., Van Vuuren, D.P., (2005) “Multi-gas abatement analysis of the Kyoto Protocol.” Report no. 550006001. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands. http://www.mnp.nl/en

Lucas, P.L., Detlef P. van Vuuren, Jos G.J. Olivier, Michel G.J. Den Elzen (2007) “Long-term reduction potential of non-CO2 greenhouse gases” environmental science & policy 10 85 – 103.

Manne, A. and R. Richels (2001), An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases. *Nature*, 410: 675-677.

Mansur, A. H., & Whalley, J. (1984). Numerical specification of applied general equilibrium models: Estimation, calibration and data. In H. E. Scarf & J. B. Shoven (Eds.), Applied General Equilibrium Analysis. Cambridge University Press

Markusen, J.R. (1975), “International Externalities and Optimal Tax Structures” *Journal of International Economics* 5, 15–29.

Mattoo, Aaditya, Arvind Subramanian, Dominique van der Mensbrugghe, and Jianwu He (2009), “Reconciling Climate Change and Trade Policy.” Peterson Institute Working Paper 09-15

McCorriston, Steve, and Ian M. Sleldon (2005), “Market Access and WTO Border Tax Adjustments for Environmental Excise Taxes Under Imperfect Competition” *Journal of Public Economic Theory*, 7 (4):579–592.

McKibben, Warwick and Peter J. Wilcoxen (2009), “The Economic and Environmental Effects of Border Tax Adjustments for Climate Policy.” Lowy Institute Working Paper 1.09

Narayanan, G. Badri and Terrie L. Walmsley, Eds. (2008), *Global Trade, Assistance, and Production: The GTAP 7 Data Base*, Center for Global Trade Analysis, Purdue University.

OECD (2008), *Climate Change Mitigation: What Do We Do?* OECD, Paris.

Okagawa, A. and K. Ban (2008), "Estimation of Substitution Elasticities for CGE Models", mimeo, Osaka University, April 2008.

Peterson, Everett and Joachim Schleich (2007), "Economic and Environmental Effects of Border Tax Adjustments", Frauenhofer Institute Working Paper. Available at http://econstor.eu/bitstream/10419/28514/1/53877794X.pdf.

Peters, P. Glen P., Robbie Andrew, James Lennox (2011), Constructing an Environmentally-Extended Multi-Regional Input-Output Table Using the GTAP Database, forthcoming in *Economic Systems Research.*

Reilly, J., M. Mayer, and J. Harnisch (2003), "Multiple Gas Control Under the Kyoto Agreement", *Environmental Modeling and Assessment*, in press; also MIT Joint Program on the Science and Policy of Global Change, Report 58.

Reilly, J., R. Prinn, J. Harnisch, J. Fitzmaurice, H. Jacoby, D. Kicklighter, J. Melillo, P. Stone, A. Sokolov, and C. Wang (1999), "Multi-gas assessment of the Kyoto Protocol", *Nature***,** 401: 549-555.

Rivers, Nic (2010), "Impacts of Climate Policy on the International Competitiveness of Canadian Industry: How Big and How to Mitigate?" *Energy Economics*. Available at http://www.sciencedirect.com/science/article/B6V7G-4Y6S7MH-2/2/2339a88ab26aef29cdf45d3452501584.

Rutherford, T.F. (1999). "Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An overview of the Modeling Framework and Syntax", *Computational Economics*, V.14, Nos. 1-2.

Rutherford, T.F. and M. Babiker, (1997) "Input-Output and General Equilibrium Estimates of Embodied Carbon: A Dataset and Static Framework for Assessment" Discussion papers in Economics No. 97-2, University of Colorado, Boulder.

Stavins, Robert (2008), A Meaningful U.S. Cap-and-Trade System to Address Climate Change, Fondazione Eni Enrico Mattei Working Paper # 241, *The Berkeley Electronic Press* (bepress). http://www.bepress.com/feem/paper241.

Tol, R.S.J., (1999) "The marginal costs of greenhouse gas emissions" *Energy Journal* 20 (1), 61–81.

US Congress, 2009. "The American Clean Energy and Security Act of 2009 (H.R. 2454)" US House of Representative, Washington, DC.

Van Vuuren, D.P., Den Elzen, M.G.J., Berk, M.M., Lucas, P.L., Eickhout, B., Eerens, H., Oostenrijk, R., (2003) "Regional costs and benefits of alternative post-Kyoto climate regimes:comparison of variants of the multi-stage and per capita convergence regimes" Report no. 728001025. National Institute for Public Health and the Environment, Bilthoven, The Netherlands. http://www.mnp.nl/en

Wiedmann, Thomas (2009), "A Review of Recent Multi-regional Input-Output Models used for Consumption-based Emission and Resource Accounting", *Ecological Economics*, 69: 211-222.

Winchester, N. (2011), "The impact of border carbon adjustments under alternative producer responses", *American Journal of Agricultural Economics*, forthcoming.

Winchester, Niven, Sergey Paltsev, and John Reilly (2010). "Will Border Carbon Adjustments Work?" MIT Joint Program on the Science and Policy of Global Change Report no. 184.

WTO CTE [World Trade Organization Committee on Trade and Environment] (1997), Taxes and Charges for Environmental Purposes: Border Tax Adjustment. Note by the Secretariat. WTO Doc. WT/CTE/W/47 of 2 May 1997.

Appendix 1: Algebraic Model Summary

The model is written as a mixed complementarity problem (MCP) as a system of nonlinear inequalities. Complementarity is a characteristic in Arrow-Debreu model rather than a condition of equilibrium. This characteristic of equilibrium allocation formulation motivates the formulation of economic models in mixed-complementarity format. The approach further permits direct integration of bottom-up activity analysis in which alternative technologies may produce one or more products subject to process oriented capacity constraints. This approach works well in cases having corner solutions. The inequalities correspond to the three sets of general equilibrium conditions: First, exhaustion of product or zero profit conditions for constant-returns-to-scale producers; second, market clearance for all goods, services and factors; third, the representative household's budget constraint. The first set determines activity levels; the second determines price levels; and the third determines the representative household's income levels. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition, and an income level to a budget constraint.

In the algebraic exposition, the notation $\prod_{gr}^{Y}$ is used to denote the unit profit function (calculated as the difference between unit revenue and unit cost) for constant-returns-to-scale (CRS) production of sector *g* in region *r* where *Y* is the name assigned to the associated production activity. Differentiating the unit profit function with respect to input and output prices provides compensated demand and supply coefficients (Hotelling's (1932) Lemma), which appear subsequently in the market clearance conditions.

The index *g* is used to denote all sectors/commodities *i* (*g*=*i*), the final consumption composite (*g*=*C*), the public good composite (*g*=*G*), and aggregate investment (*g*=*I*). The index *r* (aliased with *s*) denotes regions. The index *EG* represents the subset of all energy goods (here: coal, refined oil, gas, electricity); the label *FF* denotes the subset of fossil fuels (here: coal, oil, gas), the set RES stands for the exhaustible fossil fuel resources (here: coal, crude oil, gas), and the set ELE represents sector electricity (here: electricity). In addition, index *nco2* denotes three non-CO2 GHGs (CH4, N2O and FGAS); *val* stands for non-CO2 GHG mitigation costs ($15, $30, $45 and $60); and *nco2src* represents the non-CO2 GHG emitted sources see Table 2. Tables A1–A6 explain the notations for variables and parameters employed within the algebraic exposition of the model.

a. Zero Profit Conditions

1. Production of goods except exhaustible fossil fuels and associated complementarity variables Y_{gr} ($g \notin RES$):

$$\Pi_{gr}^{Y} = p_{gr} - \Bigg[\sum_{nco2}\sum_{nco2src} pz_{nco2,nco2src,g,r}\, a_{nco2,nco2src,g,r}^{PNCO2}$$
$$+ \Bigg[\theta_{gr}^{M} p_{gr}^{M\left(1-\sigma_{gr}^{KLEM}\right)} + \left(1-\theta_{gr}^{M}\right)\Big[\theta_{gr}^{E} p_{gr}^{E\left(1-\sigma_{gr}^{KLE}\right)}$$
$$+ \left(1-\theta_{gr}^{E}\right) p_{gr}^{KL\left(1-\sigma_{gr}^{KLE}\right)}\Big]^{\left(1-\sigma_{gr}^{KLEM}\right)/\left(1-\sigma_{gr}^{KLE}\right)}\Bigg]^{1/\left(1-\sigma_{gr}^{KLEM}\right)}\Bigg]$$
$$\leq 0$$

Where the price of the composite output Y_{gr} is defined as follows

$$p_{gr} = p_{gr}^{Y} + \sum_{nco2}\sum_{nco2src}\sum_{val} mur_{nco2,nco2src,val,g,r}\,\beta_{nco2,nco2src,val,g,r}\, a_{nco2,nco2src,g,r}^{PNCO2}$$

2. Sector-specific material aggregate and associated complementarity variables M_{gr}:

$$\Pi_{gr}^{M} = p_{gr}^{M} - \left[\sum_{i \notin EG} \theta_{igr}^{MN}\, p_{ir}^{A\left(1-\sigma_{gr}^{M}\right)}\right]^{1/\left(1-\sigma_{gr}^{M}\right)} \leq 0$$

3. Sector-specific energy aggregate and associated complementarity variables E_{gr} ($g \notin RES$):

$$\Pi_{gr}^{E} = p_{gr}^{E} - \Bigg[\sum_{i \in ELE} \theta_{igr}^{ELE}\, p_{ir}^{A\left(1-\sigma_{gr}^{ELE}\right)}$$
$$+ \sum_{i \in FF} \theta_{igr}^{FF}\left[p_{ir}^{A} + p_{r}^{CO2} a_{igr}^{CO2} + p_{r}^{NCO2} a_{igr}^{FNCO2}\right]^{\left(1-\sigma_{gr}^{ELE}\right)}\Bigg]^{1/\left(1-\sigma_{gr}^{ELE}\right)} \leq 0$$

4. Sector-specific value-added aggregate and associated complementarity variables KL_{gr} ($g \notin RES$):

$$\Pi_{gr}^{KL} = p_{gr}^{KL} - \left[\theta_{gr}^{V} v_{r}^{\left(1-\sigma_{gr}^{KL}\right)} + \left(1-\theta_{gr}^{V}\right) w_{r}^{\left(1-\sigma_{gr}^{KL}\right)}\right].$$

5. Production of exhaustible fossil fuels and associated complementarity variables Y_{gr} ($g \in RES$):

$$\Pi^{Y}_{gr} = p_{gr} - \left[\sum_{nco2} \sum_{nco2src} pz_{nco2,nco2src,g,r} a^{PNCO2}_{nco2,nco2src,g,r} \right.$$

$$+ \left[\theta^{Q}_{gr} q_{gr}^{\left(1-\sigma^{Q}_{gr}\right)} + \left(1 - \theta^{Q}_{gr}\right) \left[\theta^{L}_{gr} w_r + \theta^{K}_{gr} v_r + \sum_{i \notin FF} \theta^{RES}_{igr} p^{A}_{ir} \right. \right.$$

$$\left. \left. \left. + \sum_{i \in FF} \theta^{RES}_{igr} \left[p^{A}_{ir} + p^{CO2}_{r} a^{CO2}_{igr} + p^{NCO2}_{r} a^{FNCO2}_{igr} \right] \right]^{\left(1-\sigma^{Q}_{gr}\right)} \right]^{1/\left(1-\sigma^{Q}_{gr}\right)} \right]$$

$$\leq 0$$

6. Armington aggregate and associated complementarity variables

$$\Pi^{A}_{ir} = p^{A}_{ir} - \left[\theta^{A}_{ir} p_{ir}^{1-\sigma^{A}_{ir}} + \left(1 - \theta^{A}_{ir}\right) p_{ir}^{IM\,(1-\sigma^{A}_{ir}} \right. .$$

7. Aggregate imports across import regions and associated complementarity variables IM_{ir}:

$$\Pi^{IM}_{ir} = p^{IM}_{ir} - \left[\Sigma_s \theta^{IM}_{isr} (p_{is} \right. .$$

8. The process related non-CO2 GHGs abatement activity and associated complementarity variables :

$$\Pi^{PNCO2}_{nco2,co2src,val,g,r} = pz_{nco2,nco2src,g,r} - p^{NCO2}_{r} \leq 0 .$$

if $val.val = 0$

$$\Pi^{PNCO2}_{nco2,co2src,val,g,r} = pz_{nco2,nco2src,g,r}$$
$$- \left[v_r val + mur_{nco2,nco2src,val,g,r} \right] \leq 0$$

if $val.val \neq 0$

b. Market Clearance Conditions

9. Labour and associated complementarity variables w_r:

$$\overline{\mathrm{L}}_{\mathrm{r}} \geq \sum_{\mathrm{g}} \mathrm{Y}_{\mathrm{gr}}^{\mathrm{KL}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{KL}}}{\partial \mathrm{w}_{\mathrm{r}}}$$

10. Capital and associated complementarity variables v_r:

$$\overline{\mathrm{K}}_{\mathrm{r}} \geq \sum_{\mathrm{g}} \mathrm{Y}_{\mathrm{gr}}^{\mathrm{KL}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{KL}}}{\partial \mathrm{v}_{\mathrm{r}}} + \sum_{\mathrm{nco2}} \sum_{\mathrm{nco2src}} \sum_{\mathrm{val}} \sum_{\mathrm{g}} \mathrm{Z}_{\mathrm{nco2,nco2src,val,g,r}} \frac{\partial \Pi_{\mathrm{nco2,nco2src,val,g,r}}^{\mathrm{PNCO2}}}{\partial \mathrm{v}_{\mathrm{r}}}$$

11. Fossil fuel resources and associated complementarity variables q_{gr} (g $\in$*RES*):

$$\overline{\mathrm{Q}}_{\mathrm{gr}} \geq \mathrm{Y}_{\mathrm{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{q}_{\mathrm{gr}}}$$

12. Material composite and associated complementarity variables :

$$\mathrm{M}_{\mathrm{gr}} \geq \mathrm{Y}_{\mathrm{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p}_{\mathrm{gr}}^{\mathrm{M}}}$$

13. Energy composite and associated complementarity variables p_{gr}^{E} (g $\in$*EG*):

$$\mathrm{E}_{\mathrm{gr}} \geq \mathrm{Y}_{\mathrm{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p}_{\mathrm{gr}}^{\mathrm{E}}}$$

14. Value-added composite and associated complementarity variables p_{gr}^{KL}:

$$\mathrm{KL}_{\mathrm{gr}} \geq \mathrm{Y}_{\mathrm{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p}_{\mathrm{gr}}^{\mathrm{KL}}}$$

15. Import composite and associated complementarity variables p_{ir}^{M}:

$$IM_{ir} \geq A_{ir} \frac{\partial \prod_{ir}^{A}}{\partial p_{ir}^{IM}}$$

16. Armington aggregate and associated complementarity variables p_{ir}^{A}:

$$\mathrm{A}_{\mathrm{ir}} \geq \mathrm{Y}_{\mathrm{gr}} \frac{\partial \prod_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p}_{\mathrm{ir}}^{\mathrm{A}}}$$

17. Commodities and associated complementarity variables p_{ir} (*g*=*i*):

$$\mathrm{Y_{ir}} \geq \mathrm{A_{ir}} \frac{\partial \Pi_{\mathrm{ir}}^{\mathrm{A}}}{\partial \mathrm{p_{ir}}} + \sum_{\mathrm{s} \neq \mathrm{r}} \mathrm{IM_{is}} \frac{\partial \Pi_{\mathrm{is}}^{\mathrm{IM}}}{\partial \mathrm{p_{ir}}}$$

18. Private consumption and associated complementarity variables $INCOME_r$ (g=C):

$$\mathrm{Y_{Cr} p_{Cr}} \geq \mathrm{w_r} \overline{\mathrm{L_r}} + \mathrm{v_r} \overline{\mathrm{K_r}} + \sum_{\mathrm{i \in RES}} \mathrm{q_{ir}} \overline{\mathrm{Q_{ir}}} + \mathrm{T_r} + \overline{\mathrm{B_r}} - \mathrm{p_{Ir}} \overline{\mathrm{I}}_{\mathrm{r}} - \mathrm{p_{Gr}} \overline{\mathrm{G}}_{\mathrm{r}} + \mathrm{p_r^{GHG}} \mathrm{GHG_r}$$

19. Public consumption and associated complementarity variables p_{gr} (g=G):

$$\mathrm{Y_{Gr}} \geq \overline{\mathrm{G_r}}$$

20. Investment and associated complementarity variables p_{gr} (g=I):

$$\mathrm{Y_{Ir}} \geq \overline{\mathrm{I_r}}$$

21. CO2 emissions and associated complementarity variables p_r^{CO2}:

$$\mathrm{CO2_r} \geq \sum_{\mathrm{g}} \sum_{\mathrm{i \in FF}} \mathrm{E_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{E}}}{\partial \left(\mathrm{p_{ir}^{A}} + \mathrm{p_r^{CO2}} \mathrm{a_{igr}^{CO2}} + \mathrm{p_r^{NCO2}} \mathrm{a_{igr}^{FNCO2}} \right)} \mathrm{a_{igr}^{CO2}}$$

22. Process related non-CO2 emissions and associated complementarity variables p_r^{NCO2}:

$$\begin{aligned} \mathrm{Non\_CO2_r} \geq & \sum_{\mathrm{g}} \mathrm{Y_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{pz_r}} + \sum_{\mathrm{g}} \mathrm{Y_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p_r^{NCO2}}} \\ & - \sum_{\mathrm{nco2}} \sum_{\mathrm{nco2src}} \sum_{\mathrm{val}} \sum_{\mathrm{g}} \mathrm{Z_{nco2,nco2src,val,g,r}} \frac{\partial \Pi_{\mathrm{nco2,nco2src,val,g,r}}^{\mathrm{PNCO2}}}{\partial \mathrm{pz_r}} \end{aligned}$$

23. GHG emissions and associated complementarity variables p_r^{GHG}:

$$\begin{aligned} \mathrm{GHG_r} \geq & \sum_{\mathrm{g}} \sum_{\mathrm{i \in FF}} \mathrm{E_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{E}}}{\partial \left(\mathrm{p_{ir}^{A}} + \mathrm{p_r^{CO2}} \mathrm{a_{igr}^{CO2}} + \mathrm{p_r^{NCO2}} \mathrm{a_{igr}^{FNCO2}} \right)} \mathrm{a_{igr}^{CO2}} + \sum_{\mathrm{g}} \mathrm{Y_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{pz_r}} \\ & + \sum_{\mathrm{g}} \mathrm{Y_{gr}} \frac{\partial \Pi_{\mathrm{gr}}^{\mathrm{Y}}}{\partial \mathrm{p_r^{NCO2}}} \\ & - \sum_{\mathrm{nco2}} \sum_{\mathrm{nco2src}} \sum_{\mathrm{val}} \sum_{\mathrm{g}} \mathrm{Z_{nco2,nco2src,val,g,r}} \frac{\partial \Pi_{\mathrm{nco2,nco2src,val,g,r}}^{\mathrm{PNCO2}}}{\partial \mathrm{pz_r}} \end{aligned}$$

TABLE A1

Indices (Sets)

g	Sectors and commodities (g=i), final consumption composite (g=C), investment composite (g=I), public good composite (g=G)
i	Sectors and commodities
$\boldsymbol{r}$ (alias s)	Regions
EG	Energy goods: Coal, refined oil, gas and electricity
FF	Fossil fuels: Coal, refined oil and gas
RES	Exhaustible energy resources: Coal, crude oil and gas

TABLE A2

Activity Variables

Y_{gr}	Production of item *g* in region *r*
M_{gr}	Material composite for item *g* in region *r*
E_{gr}	Energy composite for item *g* in region *r*
$\mathrm{KL}_{\mathrm{gr}}$	Value-added composite for item *g* in region *r*
A_{ir}	Armington aggregate of commodity *i* in region *r*
$\mathrm{IM}_{\mathrm{ir}}$	Aggregate imports of commodity *i* and region *r*
$\mathrm{Z}_{\mathrm{nco2,nco2src,val,g,r}}$	Process related non-CO2 emissions by gas *nco2*, emitted source *nco2src* and cost *val* for demand category *g* in region *r*

TABLE A3

Price Variables

p_{gr}	Price of composite item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{Y}}$	Price of item *g* in region r
$\mathrm{mur}_{\mathrm{nco2,nco2src,val,g,r}}$	Premium of process-related non-CO2 abatement capacity for non-CO2 gas *nco2*, emitted source *nco2src*, demand category *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{M}}$	Price of material composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{E}}$	Price of energy composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{gr}}^{\mathrm{KL}}$	Price of value-added composite for item *g* in region *r*
$\mathrm{p}_{\mathrm{ir}}^{\mathrm{A}}$	Price of Armington good *i* in region *r*
$\mathrm{p}_{\mathrm{ir}}^{\mathrm{IM}}$	Price of import composite for good *i* in region *r*

w_r	Price of labour (wage rate) in region *r*
v_r	Price of capital services (rental rate) in sector *i* and region *r*
q_{gr}	Rent to exhaustible fossil fuel resource in region *r* (*g* ∈ RES)
p_r^{CO2}	CO2 value in region *r*
p_r^{NCO2}	Non-CO2 value in region *r*
p_r^{GHG}	GHG value in region *r*
$pz_{nco2,nco2src,g,r}$	Process related non-CO2 value for non-CO2 gas *nco2*, emitted source *nco2src*, demand category *g* in region *r*

TABLE A4
Endowments and Emissions Coefficients

$\overline{L_r}$	Aggregate labour endowment for region *r*
$\overline{K_r}$	Capital endowment of sector *i* in region *r*
$\overline{I_r}$	Capital investment in region *r*
$\overline{Gr}$	Government expenditure in region *r*
T_r	Net lump sum tax revenue in region *r*
$\overline{Q_{gr}}$	Endowment of exhaustible fossil fuel resources *g* for region *r* (g∈RES)
$\overline{B_r}$	Initial balance of payment deficit or surplus in region *r* (note: $\sum_r \overline{B}_r = 0$)
$CO2_r$	Endowment of CO2 emission rights in region *r*
Non_CO2_r	Endowment of process related non-CO2 emission rights in region *r*
GHG_r	Endowment of GHG emission rights in region *r*
a_{igr}^{CO2}	CO2 emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)
a_{igr}^{FNCO2}	Non-CO2 emissions coefficient for fossil fuel *i* in demand category *g* of region *r* ($i \in FF$)
$a_{nco2,nco2src,g,r}^{PNCO2}$	Non-CO2 emissions coefficient for *nco2* emitted by sources *nco2src* in demand category *g* of region *r*
$\beta_{nco2,nco2src,val,g,r}$	Abatement fraction at each cost category for each source

TABLE A5
Cost Shares

θ_{gr}^{M}	Cost share of the material composite in production of item *g* in region *r*
θ_{gr}^{E}	Cost share of the energy composite in the aggregate of energy and value-added of item *g* in region *r*
θ_{igr}^{MN}	Cost share of the material input *i* in the material composite of item *g* in region *r*
θ_{igr}^{ELE}	Cost share of the electricity input *i* in the energy composite of item *g* in region *r* ($i \in ele$)
θ_{igr}^{FF}	Cost share of the fossil fuel input *i* in the energy composite of item *g* in region *r* ($i \in FF$)

θ^{V}_{gr}	Cost share of capital within the value-added of item *g* in region *r*
θ^{Q}_{gr}	Cost share of exhaustible energy resource in exhaustible fossil fuel production ($g \in RES$) of region *r*
θ^{L}_{gr}	Cost share of labour in non-resource inputs to exhaustible fossil fuel production ($g \in RES$) of region *r*
θ^{K}_{gr}	Cost share of capital in non-resource inputs to exhaustible fossil fuel production ($g \in RES$) of region *r*
θ^{RES}_{igr}	Cost share of good *i* in non-resource inputs to exhaustible fossil fuel production ($g \in RES$) of region *r*
θ^{A}_{ir}	Cost share of domestic output *i* within the Armington item i of region *r*
θ^{M}_{isr}	Cost share of exports of good *i* from region *s* in the import composite of good *i* in region *r*

TABLE A6
Elasticities

σ^{KLEM}_{g}	Substitution between the material composite and the energy-value-added aggregate in the production of item *g* in region *r*[*]
σ^{KLE}_{g}	Substitution between energy and the value-added nest of production of item *g* in region *r*[*]
σ^{M}_{g}	Substitution between material inputs within the energy composite in the production of item *g* in region *r*[*]
σ^{KL}_{g}	Substitution between capital and labour within the value-added composite in the production of item *g* in region *r*[*]
σ^{E}_{gr}	Substitution between energy inputs within the energy composite in the production of item *g* in region *r* (by default: 0.5)
σ^{Q}_{gr}	Substitution between natural resource input and the composite of other inputs in exhaustible energy production ($g \in$ RES) of region *r* (calibrated consistently to exogenous supply elasticities)
σ^{A}_{ir}	Substitution between the import composite and the domestic input to Armington production of good *i* in region *r*[**]
σ^{IM}_{ir}	Substitution between imports from different regions within the import composite for good *i* in region *r*[**]

Notes:

[*] see Okagawa and Ban (2008); [**] see Narayanan and Walmsley (2008).

Appendix 2: Regional mapping Scheme

Abbreviation	Regions in the model	Regions in GTAP database
CHN	China	China, Hong Kong
JPN	Japan	Japan
IND	India	India
BRA	Brazil	Brazil
USA	United States	United States
RUS	Russia	Russia
EUR	EU27 plus EFTA	France, Germany, Italy, United Kingdom, Austria, Belgium, Denmark, Finland, Greece, Ireland, Luxembourg, Netherlands, Portugal, Spain, Sweden, Czech Republic, Hungary, Malta, Poland, Romania, Slovakia, Slovenia, Estonia, Latvia, Lithuania, Bulgaria, Cyprus, Switzerland, Norway, Rest of EFTA
RAX	Other Annex I except RUS	Belarus, Ukraine, Australia, New Zealand, Turkey, Canada
RA1	RAX plus Japan	RAX plus Japan
EEX	Energy exporting countries (excluding Mexico)	Albania, Armenia, Argentina, Azerbaijan, Botswana, Belarus, Chile, Colombia, Costa Rica, Estonia, Georgia, Guatemala, Croatia, Kazakhstan, Republic of Korea, Sri Lanka, Morocco, Mauritius, Mexico, Panama, Peru, Philippines, Paraguay, Thailand, Tunisia, Turkey, Uruguay, South Africa, Rest of Oceania, Rest of South America, Rest of Central America, Caribbean, Rest of South African Customs Union
MIC	Other middle income countries	Bangladesh, Ethiopia, Kyrgyzstan, Cambodia, Lao People's Democratic Republic, Madagascar, Malawi, Mozambique, Nicaragua, Pakistan, Senegal, Tanzania United Republic of, Uganda, Viet Nam, Zambia, Zimbabwe, Rest of South Asia, Rest of Southeast Asia, Rest of Eastern Europe, Rest of Former Soviet Union, Rest of Western Africa, Central Africa, Central African Republic, Rest of Eastern Africa, Rest of East Asia
LIC	Other low income countries	Albania, Armenia, Argentina, Azerbaijan, Botswana, Belarus, Chile, Colombia, Costa Rica, Estonia, Georgia, Guatemala, Croatia, Kazakhstan, Republic of Korea, Sri Lanka, Morocco, Mauritius, Mexico, Panama, Peru, Philippines, Paraguay, Thailand, Tunisia, Turkey, Uruguay, South Africa, Rest of Oceania, Rest of South America, Rest of Central America, Caribbean, Rest of South African Customs Union

Appendix 3: Mapping of Sectors of the model

Sectors in the model	Sectors in GTAP database
Agricultural products (AGR)	Sugar cane, sugar beet, Bovine cattle, sheep and goats, horses, Forestry, Fishing, Cereal grains nec, Animal products nec, Crops nec, Oil seeds, Paddy rice, Plant-based fibers, Raw milk, Vegetables, fruit, nuts, Wheat, Wool, silk-worm cocoons.
All other goods (AOG)	Transport equipment, Other machinery, Mining, Beverages and tobacco products, Bovine meat products, Dairy products, Food products nec, Meat products nec, Processed rice, Sugar, Vegetable oils and fats, Wood and wood-products, Construction, Textiles-wearing apparel-leather, Other manufacturing, Dwellings
Coal transformation (COL)	Coal
Chemical industry (CRP)	Chemical, rubber, plastic products
Crude oil (CRU)	Oil
Natural gas works (GAS)	Gas, Gas manufacture, distribution
Electricity and heat (ELE)	Electricity
Paper-pulp-print (PPP)	Paper-pulp-print
Commercial and public services (SER)	Communication, Insurance, Business services nec, Financial services nec, Public Administration, Defense, Education, Health, Recreational and other services, Trade, Water.
Transport (TRN)	Air transport, Water transport, and Other transport
Energy intensive and trade exposed sectors (EITE)	
Iron and steel industry (I_S)	Ferrous metals
Non-ferrous metals (NFM)	Metals nec.
Non-metallic minerals (NMM)	Mineral products nec
Refined oil products (OIL)	Petroleum, coal products

Source: Authors Own Classification (from GTAP database version 7).