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Climate-Linked Tariffs: Practical Issues[1]

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Climate-Linked Tariffs: Practical Issues[*]

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Abstract

Climate policy measures producing a meaningful reduction in greenhouse gas emissions will affect competitiveness of energy-intensive industries. Analysts asked to assess the economic impact of these policies must choose among several analytical frameworks. Input-output, partial equilibrium and general equilibrium models are all possible choices.

In this paper the GTAP 7.1 dataset is used to parameterize two models: (i) a multi-regional input-output model which assesses the "carbon footprint" of goods produced throughout the world, and (ii) a static multiregional general equilibrium model based on empirical estimates of import demand functions for goods produced in different regions. Calculations demonstrate that multi-regional input-output models, while providing useful assessments of carbon intensities, can provide a misleading sense of the potential effectiveness of border measures to deter carbon emissions in unconstrained countries.

We calculate the *carbon yield* for a climate policy regime with border tax adjustments, a value which relates realized abatement to the implicit carbon-footprint associated with bilateral trade flows. In multi-regional trade models with estimated trade elasticities, carbon yields rarely exceed 60%. For China, the most important contributor to leakage, the carbon yield is on the order of 10%.

Keywords: climate policy, border tax adjustments, international environmental agreements, carbon leakage.

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1 Introduction

Carbon leakage describes the extent to which emission-intensive production relocates outside of regulatory borders in response to climate policy (See, e.g., Miller and Blair [1985], Felder and Rutherford [1993] or Perroni and Rutherford [1993]). Most leakage estimates are based on economic models in which prices play a central role in determination of supply and demand. Most commonly, these are multiregional general equilibrium models (MR-GE), but there are also sector-specific studies which would are multi-regional partial equilibrium (MR-PE). The common idea in these models is that trade flows respond to relative prices, and carbon policy in a subset of countries thereby influences carbon emissions throughout the world.

Many empirical inputs are required for multiregional economic equilibrium analysis. These models combine data from input-output tables, international trade flows, and assumptions about elasticities of substitution and transformation. Typically, such models are based on an assumption of perfect competition and constant or decreasing returns to scale. Subject to these assumptions, the economic equilibrium framework produces theory-consistent, quantitative descriptions of the world economy. The typical analysis proceeds by simulating the effects of counterfactual climate policies and developing insights about the magnitude and pattern of carbon leakage produced by a given policy.

A separate but related line of inquiry has developed in the literature on life cycle analysis (LCA). In the LCA literature, the multiregional input-output (MR-IO) model is a commonly employed analytic framework. Practitioners of MR-IO focus on the precise calculation of full (direct plus indirect) environmental consequences of economic activities. In the context of climate change policy, MR-IO studies provide quantitative measures of the carbon intensity (the "carbon footprint") of goods made in different countries. The connection to the economic studies of carbon leakage is sometimes unclear. MR-IO estimates can be misinterpreted as estimates of the amount by which global carbon emissions decline per unit reduction in commodity imports.

Price-responsive MR-GE models involve solution of nonlinear systems of equations, and this can limit model dimensionality. MR-IO studies typically involve a larger number of good describing the existing production techniques used in industries. MR-IO models thus track energy usage with higher resolution than the typical price-equilibrium model. However, the MR-IO model lacks a behavioral basis for predictions about the pattern of adjustment in the economy in response to climate policies. The implicit assumption underlying MR-IO studies of carbon leakage is that there is no change in the carbon intensity of production or consumption in response to policy.

The present paper first argues that MR-IO provides a false sense of precision regarding our ability to calculate the externalities associated with imports of energy-intensive products. The relevant measure of carbon content should be based on the marginal impact of the green tariff. The fact that an input-output model accounts for bilateral trade flows does not mean that the resulting carbon content measures have any policy relevance. Second, the paper assess the claim typically provided by LCA studies that a large dimensional dataset is required to evaluate carbon intensity and leakage. We compute policy assessments with several datasets of differing dimension and find remarkable robustness of the findings with models ranging from 8 to 59 sectors. There are relatively few highly energy intensive sectors, and provided that a model accounts for trade flows in the key industries (e.g., oil, coal, natural gas, petroleum products, electricity, ferrous and non-ferrous metals, plastics, cement), the numerical results are robust.

Analyses based on both MR-GE and MR-IO approaches are regularly consulted by policymakers in the process of designing climate policies, so it is important to understand the relationship between the two tools to the extent that they lead to different policy prescriptions. This paper illustrates MR-IO and MR-GE methods with a common dataset – the most recently released update of the GTAP 7.1 database which features a 2004 base year and a set of econometrically estimated trade elasticities.

The policy simulations in this paper are not intended to portray a specific policy proposal but rather the range of abatement measures which have been discussed during recent months. We thus contemplate a 20% cut back in carbon emissions by a set of coalition states listed in Table 1. Most of these countries are included explicitly in the G20 and a composite Rest-of-Europe region. We compare this equilibrium with a border tax adjustment (BTA) simulation in which tariffs are applied to inputs from all non-coalition states with border taxes are calculated on the

Table 1: Assumed Coalition Regions

ANZ	Australia and New Zealand
CAN	Canada
USA	United States
DEU	Germany
FRA	France
GBR	United Kingdom
ITA	Italy
EUR	Rest of European Union
JPN	Japan

basis of the carbon permit price in the importing country and the MR-IO-based carbon content of goods produced in the non-coalition states.

The BTA scenario illustrates the environmental ineffectiveness of border measures. Such measures reduce cost of abatement for coalition states but largely at the expense of terms of trade changes which impoverish non-coalition countries.

Equilibrium responses can be used to calculate the *carbon yield* of border tax adjustment. Carbon yield is defined as the ratio between the MR-GE and idealized MR-IO-based change in carbon emissions associated with a given reduction in bilateral trade. In multi-regional trade models with empirically-estimate trade elasticities, carbon yields rarely exceed 60%. For China, the model important contributor to leakage, the carbon yield is on the order of 10%.

2 Literature

Many studies focusing on the impact and potential magnitude of carbon leakage undertaken in the last 20 years. A number focus on legal issues surrounding the problem [Pauwelyn 2007, Houser et al. 2008, Howse and Eliason 2008]. On the policy level, leakage and competitiveness issues related to energy intensive and trade-exposed industries are currently being discussed in the proposed climate legislation in the U.S. [S.1733 2010] and within the E.U.'s climate policy debate [of the European Communities 2009]

The main conclusion of the legal literature is that leakage is a contentious issue and we need to be careful and avoid new trade wars. The main conclusion of the policy-focused analysis is that competitiveness issues are politically more potent than leakage.

Concerning quantification, some studies have relied on historical data [Aldy and Pizer 2009] while others have focused on specific sectors (Demailly and Quirion [2004], Gielen and Moriguchi [2002], Lanz et al. [2010]) using partial equilibrium analysis. Finally, a whole range of studies have taken advantage of global trade datasets (mostly the GTAP database):

- Input-output analysis is widely used for the estimation of indirect emissions embodied in production [Miller and Blair 1985], and emissions embedded in trade (EET) (see Peters and Hertwich [2008] or Wyckoff and Roop [1994]). Peters [2008] gives a detailed description of how to account for trade and build consumption-based carbon inventories relying on the GTAP database. He distinguishes between the emissions embodied in bilateral trade (EEBT) (or bilateral trade input-output), in which intermediate imports are not taken into account and the multi-region input-output approach (MR-IO) used here, in which the carbon content of intermediate imports is endogenized, and gives a exhaustive comparison of the two approaches.

- Multiregional equilibrium analysis using the same data, there have been studies based on partial equilibrium analysis [Fisher and Fox 2009], and full computable general equilibrium analysis [Paltsev 2000, Babiker and Rutherford 2005, Warwick J and Wilcoxen 2008, Ho et al. 2008, Mattoo et al. 2009].

In short, the findings seem to be that leakage rates are mostly modest (generally are in the 10% to 30% range). Additionally, it is estimated that a large part of this leakage will be caused by decreased pressure on global fossil fuel price, and not through direct production displacement, hence the justification for the definition of ”weak” carbon leakage [Peters 2008], which takes in account only the increase in emissions embodied in the exports of carbon-constrained to non carbon-constrained economies.

Also, some have pointed out (Warwick J and Wilcoxen [2008], Fisher et al. [2010]) that the modest leakage rates coming out of general equilibrium analysis might at least partially be explained by the high level of sectoral aggregation which characterizes the studies available to date, as leakage effects are more pronounced in highly carbon-intensive sectors, but these effects may be drowned-out in very large aggregate sectors.

3 The GTAP 7 Dataset and Model

The Global Trade Analysis Project (GTAP) is a research program initiated in 1992 to provide the economic research community with a global economic dataset for use in the quantitative analyses of international economic issues. The project's objectives include the provision of a documented, publicly available, global, general equilibrium data base, and to conduct seminars on a regular basis to inform the research community about how to use the data in applied economic analysis. GTAP has lead to the establishment of a global network of researchers who share a common interest of multi-region trade analysis and related issues. The GTAP research program is coordinated by Professor Thomas Hertel, Director of the Center for Global Trade Analysis at Purdue University. As Deputy Director of this Center, Robert McDougall oversees the data base work. Software development within the GTAP project has been assisted greatly by the efforts of Ken Pearson, Mark Horridge and other Australian researchers from Centre of Policy Studies, Monash University. (See Hertel [1997] and McDougall [2005]). A list of applications based on the GTAP framework can be found at the GTAP home page, (HTTP://WWW.GTAP.ORG).

The GTAP version 7.1 database, released in May, 2010, represents global production and trade for 113 country/regions, 57 commodities and 5 primary factors. The data characterize intermediate demand and bilateral trade in 2004, including tax rates on imports and exports and other indirect taxes. [1]

For our purposes, we begin with an aggregation of the underlying database which provides an explicit representation of the G20 countries and two aggregate regions representing non-G20 world. We use the database first as the basis for MR-IO assessment of the direct and indirect carbon content of goods produced in different countries. We then employ the MR-IO-based carbon intensities to evaluate the economic consequences of border measures in a corresponding

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[1] A guide to what's new in GTAP7 can be found in [Narayanan and Dimaranan 2008].

multi-regional general equilibrium model. [2]

The core GTAP model is a static, multi-regional model which tracks the production and distribution of goods in the global economy. In GTAP the world is divided into regions (typically representing individual countries), and each region's final demand structure is composed of public and private expenditure across goods. The model is based on optimizing behavior. Consumers maximize welfare subject to budget constraint with fixed levels of investment and public output. Producers combine intermediate inputs, and primary factors (skilled and unskilled labor, land, resources and physical capital) at least cost subject for given technology. The dataset includes a full set of bilateral trade flows with associated transport costs, export taxes and tariffs.

3.1 Benchmark Data and Accounting Identities

The economic structure underlying the GTAP dataset and model is illustrated in Figure 1. Symbols in this flow chart correspond to variables in the economic model. Y_{ir} portrays the production of good i in region r, C_r, I_r and G_r portray private consumption, investment and public demand, respectively. M_{jr} portrays the import of good j into region r. HH_r and $GOVT_r$ stand for representative household and government consumers.

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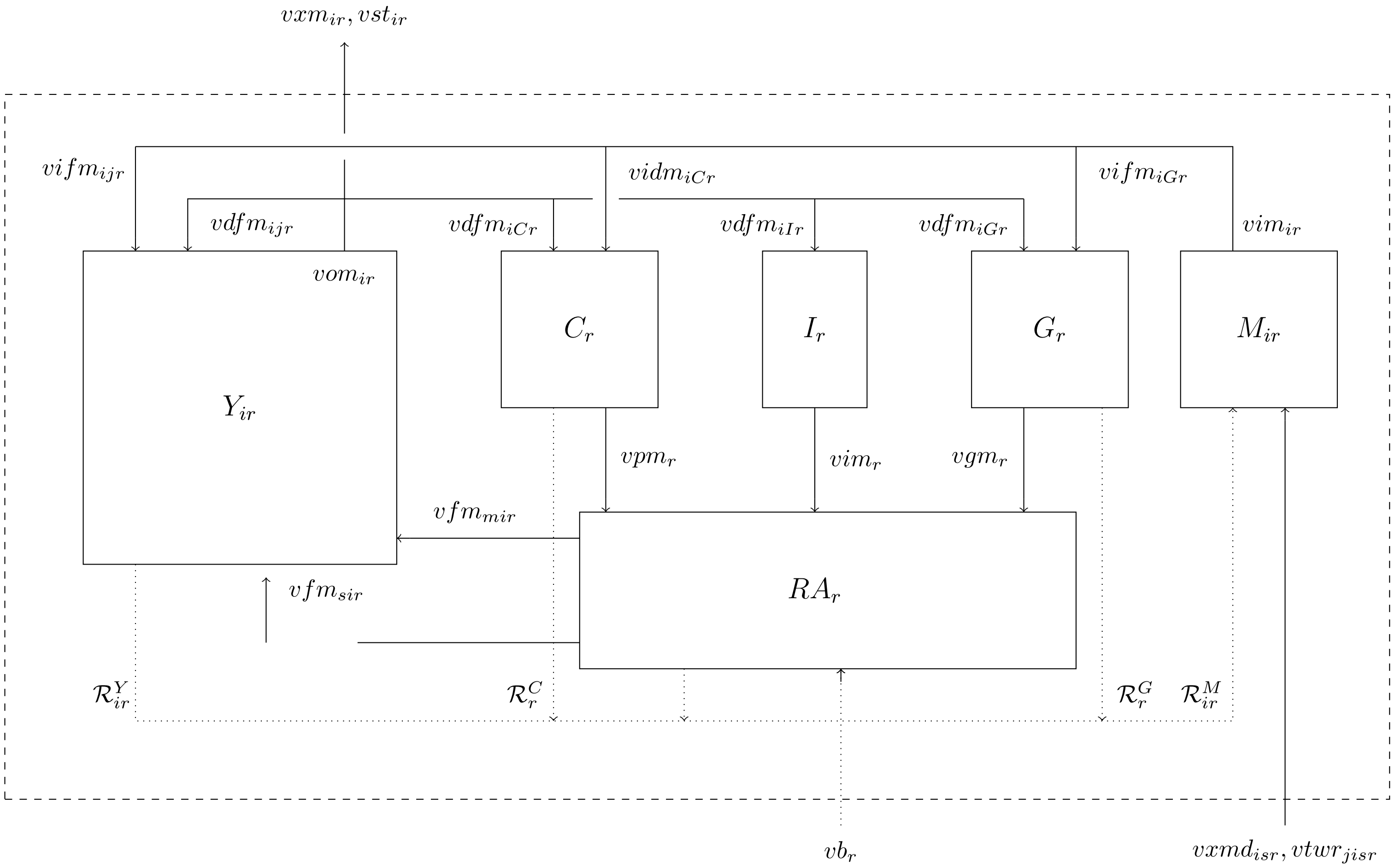
[2] *A methodological note:* The principal programming language for GTAP data and modeling work is GEMPACK [Harrison and Pearson 1996]. In the GEMPACK framework the model is solved as a system of nonlinear equations. The present paper describes a version of the GTAP model which has been implemented in GAMS. The GAMS model is essentially implemented as a nonlinear system of equations, although it can be posed either as a CNS or MCP. There are a few substantive differences between the GEMPACK and GAMS version of the model. One of these is the final demand system. Whereas the GEMPACK model is based on a CDE demand system, the GAMS model employs Cobb-Douglas preferences. Second, there are differences in units of account. Values in the GAMS implementation differ from the GEMPACK model by a factor of 1000. The GTAP database measures all transactions in millions of dollars whereas GTAP7inGAMS measures transactions in billions of dollars. Third, the two models differ in their representation of investment demand and global capital markets. The GEMPACK model assumes that a "global bank" allocates international capital flows in response to changes in regional rates of return. The GTAP7inGAMS model makes the simplest possible assumptions regarding investment demand, international capital flows and the time path of adjustment: all of these variables are exogenously fixed at base year levels.

Figure 1: GTAP7 Benchmark Flows



In this figure commodity and factor market flows appear as solid lines. Domestic and imported goods markets are represented by horizontal lines at the top of the figure. Domestic production (vom_{ir}) is distributed to exports ($vxmd_{irs}$), international transportation services (vst_{ir}), intermediate demand ($vdfm_{ijr}$), household consumption ($vdpm_{ir}$), investment ($vdipm_{ir}$)and government consumption ($vdgm_{ir}$). The accounting identity on the output side:

$$\underbrace{vom_{ir}}_{\text{Value of Output}} = \sum_s \underbrace{vxmd_{irs}}_{\text{Bilaterl exports}} + \underbrace{vst_{ir}}_{\text{Transport exports}} + \sum_j \underbrace{vdfm_{ijr}}_{\text{Intermediate Demand}} + \underbrace{vdpm_{ir} + vdim_{ir} + vdgm_{ir}}_{\text{Final Demand (C + I + G)}}$$

The value of output is in turn related to the cost of intermediate inputs, value-added, and tax revenue:

$$\underbrace{vom_{ir}}_{\text{Value of Output}} = \underbrace{\sum_j vifm_{jir} + vdfm_{jir}}_{\text{Intermediate Inputs}} + \underbrace{\sum_f vfm_{fir}}_{\text{Factor Earnings}} + \underbrace{\mathcal{R}^Y_{ir}}_{\text{Tax Revenue}} \tag{1}$$

Imported goods which have an aggregate value of vim_{ir} enter intermediate demand ($vifm_{jir}$), private consumption ($vipm_{ir}$) and public consumption ($vigm_{ir}$). The accounting identity on the output side for these flows is thus:

$$\underbrace{vim_{ir}}_{\text{Value of Imports}} = \underbrace{\sum_j vifm_{ijr}}_{\text{Intermediate Demand}} + \underbrace{vipm_{ir} + vigm_{ir}}_{\text{Final Demand (C+G)}}$$

and the accounting identify relating the value of imports to the cost of associated inputs is:

$$\underbrace{vim_{ir}}_{\text{CIF Value of Imports}} == \underbrace{\sum_s vxmd_{isr} + \sum_j vtwr_{jisr}}_{\text{FOB Exports + Transport Cost}} + \underbrace{\mathcal{R}^M_{ir}}_{\text{Tariffs Net Subsidies}} \tag{2}$$

Part of the cost of imports includes the cost of international transportation services, $vtwr$. These services are provided with inputs from regions throughout the world, and the supply demand balance in the market for transportation service j requires that the sum across all regions of service exports (vst_{ir}, at the top of the figure) equals the sum across all bilateral trade flows of service inputs ($vtwr_{jisr}$ at the bottom of the figure):

$$\underbrace{\sum_{r} vst_{jr}}_{\text{Service } j \text{ Exports}} = \underbrace{\sum_{isr} vtwr_{jisr}}_{\text{Transport Demand for } j} \tag{3}$$

Carbon emissions associated with fossil fuels are represented in the GTAP database through a sattelite data table ($eco2_{igr}$) constructed on the basis of energy balances from the International Energy Agency. These emissions are proportional to fossil fuel use (commodities OIL, GAS, and COL).

Given detailed emissions associated with fossil fuel use, we can calculate direct carbon emissions associated with the production of good g in region r as:

$$\underbrace{co2e_{gr}}_{\text{Aggregate Carbon}} = \underbrace{\sum_{i} eco2_{igr}}_{\text{Sum of Carbon in Fuel Inputs}}$$

where $eco2_{igr}$ is the IEA-based statistics describing carbon emissions associated with the input of fuel i in the production of good g in region r.

3.2 Two Models Based on GTAP 7

This paper employs two fairly "generic" models based on the GTAP7.1 dataset. The first is a multi-regional input-output model which is employed to calculate the aggregate carbon content of goods produced in different regions of the world. This multi-regional input-output model is processed as a system of linear equations which may either be solved directly or iteratively.

The second model developed for this paper is a multi-regional general equilibrium model in which value shares and most elasticities are based on values from the GTAP database. A few additional assumptions are required to account for the representation of energy-economy interactions. These include *own-price elasticities of supply* for crude oil, coal and natural gas, *price elasticities of demand* for energy, trade elasticities and elasticities of substitution among energy goods (electricity, refined oil, coal, and natural gas).

3.2.1 A Multi-Regional Input-Output Model

Variables characterizing the MR-IO model include:

x^y_{gr}	Carbon content of produced goods, C, I and G.
x^m_{ir}	Carbon content of imported commodity i (weighted average)
x^t_j	Carbon content of international trade services

The multiregional input-output model includes a set of accounting identities conforming to the GTAP dataset identities. For example, the composite carbon embodied in the output of good i in region r follows from equation (1):

$$\underbrace{x^y_{gr}\ vom_{gr}}_{\text{Total Embodied Carbon}} = \underbrace{co2e_{gr}}_{\text{Direct Carbon}} + \underbrace{\sum_i x^m_{ir}\ vifm_{igr}}_{\text{Indirect Imported}} + \underbrace{\sum_i x^y_{ir}\ vdfm_{igr}}_{\text{Indirect Domestic}}$$

The carbon content of imports then follows from equation (2):

$$\underbrace{x^m_{ir}\ vim_{ir}}_{\text{Carbon Embodied in Imports}} = \underbrace{\sum_s x^y_{is}\ vxmd_{isr}}_{\text{Carbon in Goods}} + \underbrace{\sum_j x^t_j\ vtwr_{jisr}}_{\text{Carbon in Transportation}}$$

Finally, the carbon content of transportation follows from the GTAP accounting identity (3):

$$\underbrace{x^t_j\ vtw_j}_{\text{Carbon Content of Transport}} = \underbrace{\sum_r x^y_{jr}\ vst_{jr}}_{\text{Carbon in Inputs}}$$

This system of equations can be abstractly represented as a linear system of the form:

$$x = b + Ax$$

and can be formulated and solved directly as a square system of equations in GAMS. Alternatively the system can be solved recursively in GAMS (or Excel), with a diagonalization procedure.

The estimate in iteration $k + 1$ is a simple refinement of the estimate in iteration k:

$$x_{k+1} = b + Ax_k$$

Iterative solution of the MR-IO model involves the following steps:

Initialize:

$$x^y_{gr} = co2e_{gr}/vom_{gr}$$

Repeat: i. Refine estimates of the carbon content of international trade services:

$$x^t_j = \frac{\sum_r vst_{jr} x^y_{jr}}{vtw_j}$$

ii. Refine estimates of the carbon content of bilateral imports:

$$x^m_{ir} = \frac{\sum_s \left(vxmd_{isr} x^y_{is} + \sum_j x^t_j vtwr_{jisr} \right)}{vim_{ir}}$$

iii. Update carbon content estimates:

$$x^y_{gr} = \frac{co2_{gr} + \sum_i x^m_{ir} vifm_{igr} + \sum_i x^y_{ir} vdfm_{igr}}{vom_{gr}}$$

3.3 The General Equilibrium Model

Variables which define a general equilibrium model based on GTAP 7.1 are summarized in the Tables 2 - 4. Table 2 defines the various dimensions which characterize an instance of the model, including the set of sectors/commodities, the set of regions, the set of factors of production. Set g is combines the production sectors i and private and public consumption demand (indices `"c"` and `"g"`) and investment demand (index `"i"`). Tables 3 and 4 display the concordance between the variables and their GAMS equivalents.

The GTAP database includes a 113 regions and 57 commodities, but dimensionality typically limits the number of regions and goods which can be included in a single model. The regions

Table 2: Set Indices

i, j	Sectors and goods, an aggregation of the 55 sectors in the GTAP 7 database
g	The union of produced goods i, private consumption `"c"`, public demand `"g"` and investment `"i"`
r	Regions, an aggregation of the 113 regions in the GTAP 7 database
f	Factors of production (consisting of *mobile factors*, $f \in m$, skilled labor, unskilled labor and capital, and specific factors corresponding to crude oil, natural gas and coal resources)[3]

Table 3: Activity Levels

Var	Description	GAMS Variable	Bmk value
Y_{ir}	Production	`Y(i,r)`	`vom(i,r)`
C_r	Aggregate consumption D	`Y("c",r)`	`vom("c",r)`
G_r	Aggregate public D	`Y("g",r)`	`vom("g",r)`
I_r	Aggregate investment D	`Y("i",r)`	`vom("i",r)`
M_{ir}	Aggregate imports	`M("i",r)`	`vim(i,r)`
YT_j	Intl. transp. services	`YT(j)`	`vtw(j)`

Table 4: Prices

p_r^C	Consumer price index
p_r^G	Public provision price index
p_{ir}^Y	Supply price, gross of indirect producer taxes
p_{ir}^M	Import price, gross of export taxes and tariffs.
p_j^T	Marginal cost of transport services
p_{fr}^F	Factor prices for labor, land and resources
p_{ir}^S	Price of the sector-specific primary factor for CRU, GAS and COL.

employed in the present study are displayed in Table 5 and sectors in the model are displayed in Table 6.

Table 3 defines the primal variables (activity levels) which define an equilibrium. The model determines values of all the variables except international capital flows, a parameter which would be determined endogenously in an intertemporal model.

Table 4 defines the relative price variables for goods and factors in the model. As is the case in any Shoven-Whalley model, the equilibrium conditions determine *relative* rather than *nominal* prices. One market equilibrium condition corresponds to each of the equilibrium prices.

Our model departs from the conventional GTAP framework with the explicit representation of energy demand and supply elasticities. Thus, while the basic equilibrium conditions (market clearance, zero-profit and income balance) are more or less identical to the GTAP7inGAMS model [Rutherford 2010], there are several differences in the nesting structure of sectoral production and private consumption where explicit substitution between energy and non-energy composites has been introduced.

The energy goods included in the model include:

Table 5: Regions in the G20 Aggregation

ANZ	Australia and New Zealand
ARG	Argentina
BRA	Brazil
CAN	Canada
CHN	China and Hong Kong
FRA	France
DEU	Germany
IND	India
IDN	Indonesia
ITA	Italy
JPN	Japan
MEX	Mexico
RUS	Russian Federation
XWS	Western Asia
ZAF	South Africa
KOR	South Korea
TUR	Turkey
GBR	United Kingdom
USA	United States
EUR	Rest of European Union
ROW	Rest of World

Table 6: Commodities in the GTAP Dataset

PDR	Paddy rice	LUM	Wood products
WHT	Wheat	PPP	Paper products, publishing
GRO	Cereal grains nec	CRP	Chemical, rubber, plastic products
V_F	Vegetables, fruit, nuts	NMM	Mineral products nec
OSD	Oil seeds	I_S	Ferrous metals
C_B	Sugar cane, sugar beet	NFM	Metals nec
PFB	Plant-based fibers	FMP	Metal products
OCR	Crops nec	MVH	Motor vehicles and parts
CTL	Bovine cattle, sheep and goats, horses	OTN	Transport equipment nec
OAP	Animal products nec	ELE	Electricity
RMK	Raw milk	OME	Machinery and equipment nec
WOL	Wool, silk-worm cocoons	OMF	Manufactures nec
FRS	Forestry	WTR	Water
FSH	Fishing	CNS	Construction
OIL	Oil	TRD	Trade
GAS	Gas	OTP	Transport nec
OMN	Minerals nec	WTP	Water transport
CMT	Bovine meat products	ATP	Air transport
OMT	Meat products nec	CMN	Communication
VOL	Vegetable oils and fats	OFI	Financial services nec
MIL	Dairy products	ISR	Insurance
PCR	Processed rice	OBS	Business services nec
SGR	Sugar	ROS	Recreational and other services
OFD	Food products nec	OSG	Public Administration, Defense, Education, Health
B_T	Beverages and tobacco products	DWE	Dwellings
TEX	Textiles	COL	Coal
WAP	Wearing apparel	CRU	Petroleum, coal products
LEA	Leather products	EEQ	Electronic equipment

CRU	Crude oil
OIL	Refined oil products
COL	Coal
GAS	Gas
ELE	Electricity

Two of these are *secondary* energy goods (refined oil and electricity), both of which are produced subject to constant returns to scale with inputs of capital, labor, energy and materials. Oil products are refined from crude, and electricity is produced with inputs of coal, natural gas and oil. Variations in dispatch of different generating units are approximated through a Cobb-Douglas aggregation of gas, coal and oil inputs.

Primary factors in the model correspond to skilled and unskilled labor, capital and energy resources. Capital and labor are intersectorally mobile whereas crude oil, gas and coal resources are sector-specific. Given specific factors, the primary fossil fuels, crude oil, coal and natural gas, are produced subject to decreasing returns to scale. Given resource rental shares (θ_{ir}) from the database, the elasticity of substitution between resources and other inputs to primary energy production are calibrated to match assumed price elasticities of supply for these three fossil fuels, using. The calibrated substitution elasticities are given by:[4]

$$\sigma_{ir} = \eta_i \frac{1 - \theta_{ir}}{\theta_i r}$$

Our equilibrium framework is based on the assumption of optimizing atomistic agents, and applies for both producers and consumers. Profit maximization in the constant returns to scale setting is equivalent to cost minimization subject to technical constraints. For sector Y_{ir} we characterize input choices as though they arose from minimization of unit production costs.

Underlying production function are represented by a nested constant-elasticity-of-substitution (CES) form in which the top-level substitution describes energy demand and a Cobb-Douglas aggregate describes trade-offs between electricity, natural gas, oil and coal. Non-energy intermediates enter as fixed-coefficients (Leontief) nest with capital-labor value-added composite in

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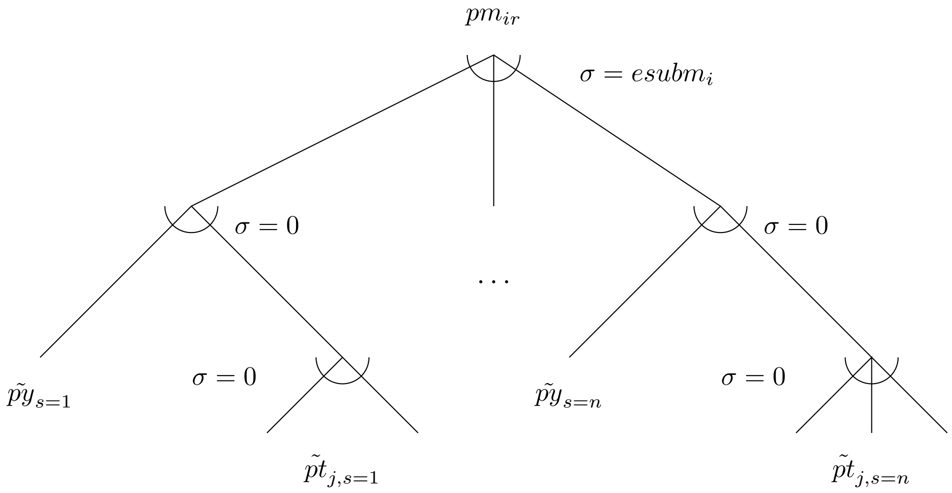
[4] The calculations presented here are based on assumed values $\eta_{\text{COL}} = 1$, $\eta_{\text{CRU}} = 0.5$, and $\eta_{\text{GAS}} = 0.25$.

Figure 2: Armington Aggregation : $M_{ir} = A_{ir}(dxmd, dtwr)$



which capital, skilled and unskilled labor are substitutable with elasticity σ_g^{KL}.

Bilateral trade flows are determined by a constant-elasticity aggregate across goods provided by different trading partners. This formulation follows Armington's idea of regionally differentiated products, but it could just as easily be interpreted as a monopolistic competition model in which the number of firms in each region is fixed.

The import aggregation function is described by the nested CES-Leontief function shown in Figure 2. Transportation services enter on a proportional basis with imports from different countries, reflecting differences in unit transportation margins across different goods and trading partners. Substitution at the top level in an Armington composite involves trading off of both imported goods and associated transportation services. Trade flows are subject to export subsidies and import tariffs, with subsidies paid by government in the exporting region, and tariffs collected by government in the importing region.

Numeric values of the elasticity of substitution across import sources as provided in the GTAP 7.1 database is presented in Figure 3. We use these values except for from the elasticity of substitution for GAS which we reduce to 10, the same value as is adopted for crude oil.

Private consumption (final demand), like production, introduces substitution between an energy composite and a non-energy composite. At the second level non-energy goods are substitutable according to a Cobb-Douglas substitution function.

Finally, international transportation services are provided as a Cobb-Douglas aggregation of transportation services exported from countries throughout the world, and both public consumption and investment demands are fixed. This formulation introduces substitution at the second level between domestic and imported inputs while holding sectoral commodity aggregates constant.

4 Simulation Results

4.1 Carbon Content

Carbon intensities are dispersed both across commodities and regions. Generally, chemicals, ferrous and non-ferrous metals and transportation services tend to be energy- and carbon-intensive. Most other commodities have substantially lower carbon content. A broad overview of carbon content is provided in Figures 4 and 5. Figure 4 is a scatter plot of global production and carbon content for commodities in the GTAP 7 database, with the exception of electricity which will be discussed below. Figure 5 is a scatter plot of global trade and carbon intensity. Carbon intensities in this figure include carbon inputs associated with international transport and are therefore slightly greater than those employed in Figure 4.

The most carbon intensive commodities are metal and mineral products, transportation services and refined energy products. The carbon intensity of oil and coal measured here only includes the embodied carbon associated with refining and mining operations, not the carbon associated with burning of these fuels.

The CRP sector in GTAP is broadly defined, representing most chemicals, pharmaceutical products, rubber and plastic products. There are a number of commodities within this sector which are highly carbon intensive, in particular petrochemical products. The database accounts for the trade and the carbon associated with these goods, but it does not differentiate with regard to the implicit impacts of policies based on carbon content.

Figure 6 illustrates the broad range of carbon intensities associated with production processes in different countries and regions of the world. Carbon contents of 16 carbon intensive goods produced in five different regions are compared here. The carbon intensity of electricity produced in China is most striking, with a value which is nearly twice that of the average value in all non-coalition regions, almost five times the average value in coalition regions, and roughly ten times the carbon intensity of electricity produced in Japan.

Figure 7 provides a decomposition of the average carbon content of goods produced in coalition and non-coalition countries. Elements of the decomposition include:

$co2e$ Carbon associated with fossil fuels employed directly in production of this commodity

$vdfm$ Carbon embodied in domestic intermediate inputs, generally representing electricity inputs,

$vifm$ Carbon embodied in imported intermediate inputs,

$vtwr$ Average carbon embodied in international transport of exports

Figure 7 omits electricity in order to improve resolution for goods which are more widely traded. While the pairwise comparison between coalition and non-coalition carbon contents is highly variable, it is generally the case that a large share of differences in carbon intensity is due to $vdfm$, corresponding to the carbon content of electricity.

Figures 8 and 9 describe the aggregate carbon content of regional trade flows. The carbon content of exports, measured on the horizontal axis, is defined as:

$$C_r^X = \sum_{i,s} \left(x_{ir}^y vxmd_{irs} + \sum_j x_j^t vtwr_{jirs} \right),$$

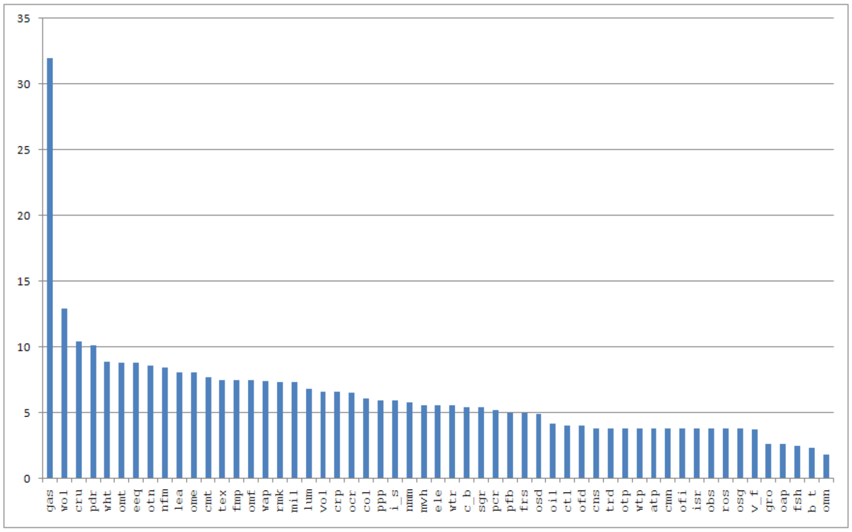
and the carbon content of imports, measured on the vertical axis, is defined as:

$$C_r^M = \sum_{i,s} \left(x_{is}^y vxmd_{isr} + \sum_j x_j^t vtwr_{jisr} \right).$$

Figures 8 and 9 are the same diagram with different scales simply to provide resolution for both large and small countries. These figures are simply a scatter plot of carbon embodied in regional imports and exports. A regional data point signified by a pink shaded box represents trade flows between a region and all non-coalition states. A data point with an unshaded box represents trade flows with coalition states. As can be seen in Figure 8, the USA, DEU, ITA, JPN, EUR and KOR import more carbon in trade with non-coalition states whereas they all engage in roughly balanced carbon trade with other coalition states. GBR and FRA import carbon from both coalition and non-coalition states while CAN imports from non-coalition states and exports to coalition states.

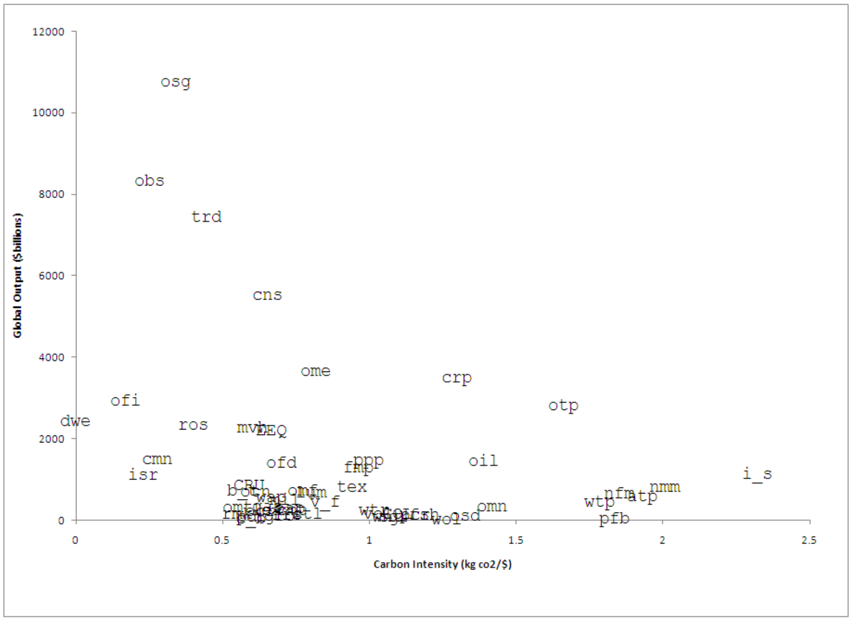
Among the non-coalition states, CHN, IND, IDN and ROW both export much more carbon than it imports in trade with coalition states, yet both run nearly balanced carbon trade with other non-coalition countries. RUS, XWS and ZAF are net carbon exporters to coalition and non-coalition states alike. MEX imports a relatively small amount of carbon from non-coalition states and runs a roughly balanced carbon trade with the coalition.

Figure 3: Armington Elasticities: σ_{MM}



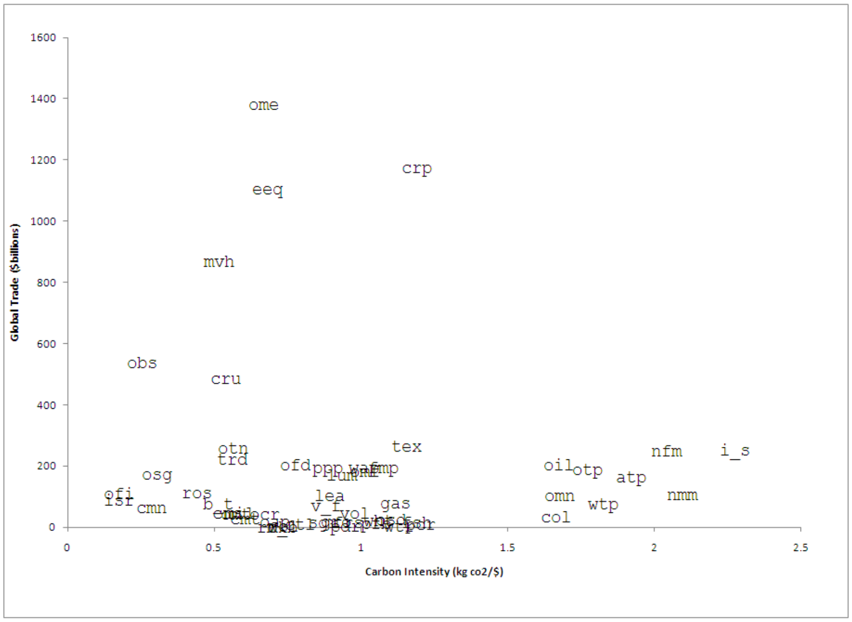
Source: GTAP 7.1 database

Figure 4: Global Production and Carbon Intensity



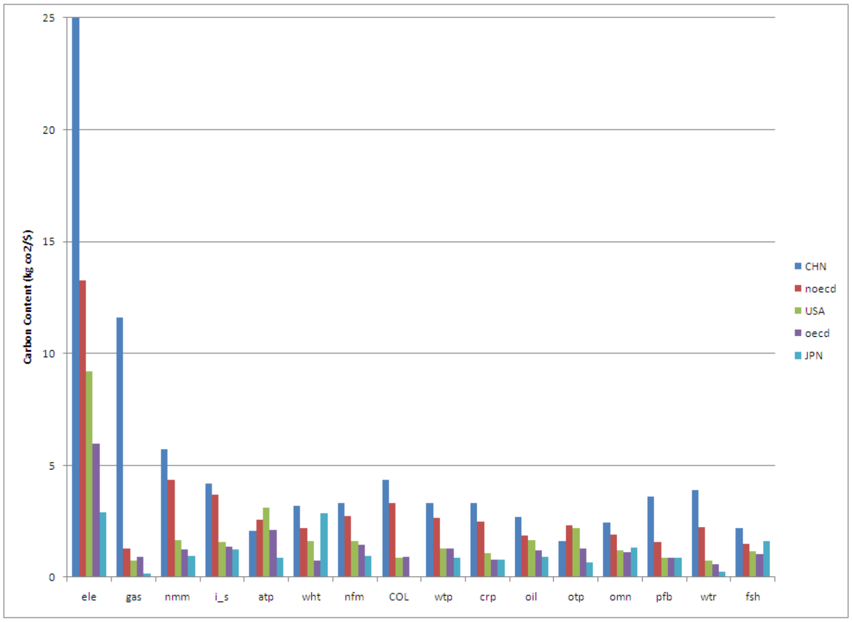
Source: MR-IO calculation with the GTAP 7.1 database

Figure 5: Global Trade and Carbon Intensity



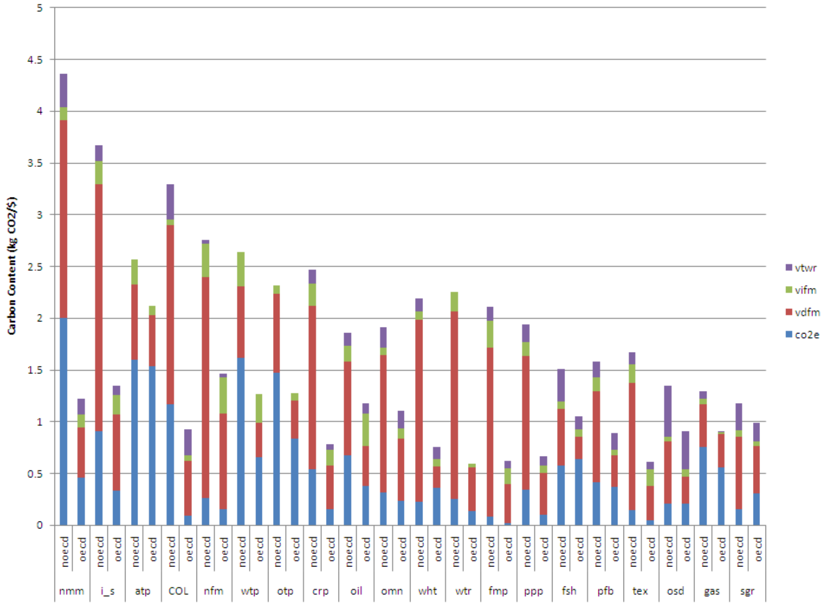
Source: MR-IO calculation with the GTAP 7.1 database

Figure 6: Carbon Content



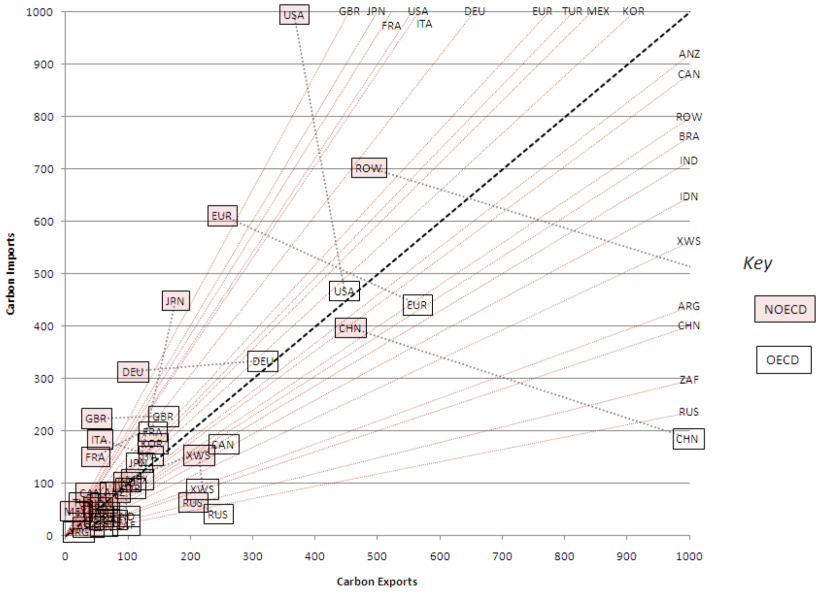
Source: MR-IO calculation with the GTAP 7.1 database

Figure 7: Direct and Indirect Carbon Content



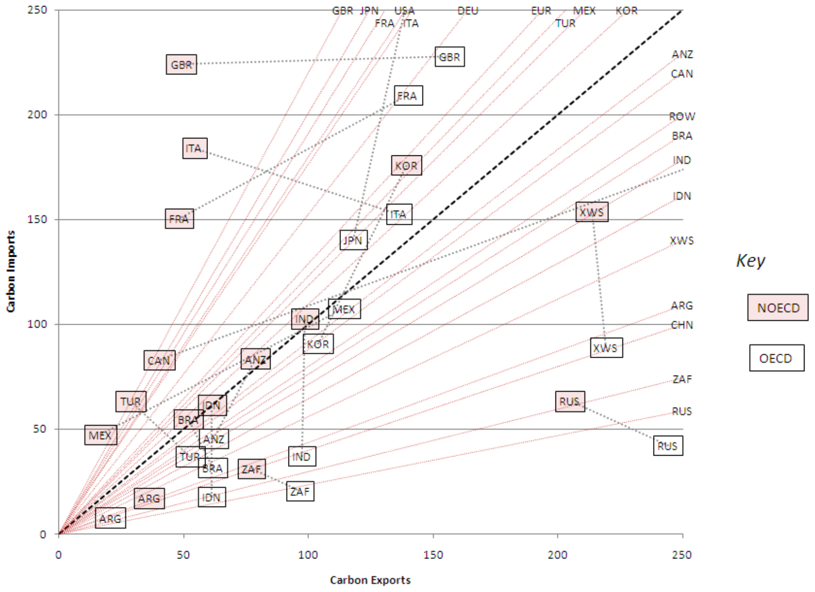
Source: MR-IO calculation with the GTAP 7.1 database

Figure 8: Embodied Carbon Trade (all countries)



Source: MR-IO calculation with GTAP 7.1 database

Figure 9: Embodied Carbon Trade (smaller countries)



Source: MR-IO calculation with the GTAP 7.1 database

4.2 General Equilibrium Simulations

The main objective in setting up parallel models was to highlight differences in perspective provided by the MR-IO and MR-GE models. The scenarios consider are therefore somewhat stylized, and we do no explore any number of alternative assumptions concerning coalition membership, permit markets, non-price abatement measures, and projections of growth in economic activity and energy demand over coming decades. Instead, we focus on a model calibrated to the here and now (base year 2004), and after replicating the benchmark equilibrium, we evaluate three counterfactual scenarios. These scenarios are defined by the following acronyms:

REF The reference case, in which coalition states reduce carbon emissions by 20% with regional taxes and/or permit markets which equalize the marginal cost of abatement across sectors within but not across coalition countries.

NB! In this and the other two scenarios, aggregate capital stocks, GDP and all other exogenous parameters remain unchanged at levels consistent with the 2004 benchmark equilibrium. This calculation involves no "forward calibration" based on assumptions regarding anticipated growth rates throughout the world. Capital, skilled and unskilled labor are mobile within but not across regions.

BTA As in REF, carbon emissions in coalition countries are reduced by 20%, and these are combined with a border tax adjustment in which tariffs are applied on bilateral imports from non-coalition states which are proportional to the regional carbon tax rate multiplied times the carbon content as calculated in the MR-IO model.

EQV An "equivalent abatement" scenario, in which emission targets in the coalition are proportionally scaled such that *global* carbon emissions are equivalent to those realized in scenario BTA.

In the absence of flexibility mechanisms, uniform abatement targets produce different marginal abatement costs. This is evidenced in Figure 10 which displays carbon taxes associated with the three abatement scenarios. The lowest marginal costs are observed in those regions with the highest share of coal, NZL, USA and CAN. The highest marginal costs are obtained in the least carbon-intensive economies, ITA, JPN, and FRA.

It is not surprising that the marginal cost of abatement increases with the border tax adjustments. These adjustments improve profitability of carbon-intensive producers in the domestic economy, and for this reason a higher carbon tax is required to meet the abatement target.

The carbon tax must be even higher in the EQV scenario. In this case, the coalition states must reduce their abatement targets in order to reach the same global carbon emissions as in BTA. This amounts to a reduction by 20.4% from benchmark.

Figures 11 and 12 report the welfare cost of abatement. In the reference case, the biggest economic losses are experienced by the energy exporting regions, RUS and XWS. These welfare costs, corresponding to between 2 and 3% of base year consumption, are a direct consequence of changes in international terms of trade. Carbon abatement lowers demands for fossil fuels, and this depresses the international price of oil, coal and natural gas, products which represent a substantial share of export earnings and GDP for RUS and XWS.

Economic losses in the REF case for the coalition member states are on the order of 0.5 % of consumption. There are small negative spillover in these cases for most of the non-coalition members except for KOR, IND and TUR which benefit from changes in terms of trade. (Energy-intensive exports are more valuable for countries outside the coalition in a carbon-constrained world.)

The distribution and magnitude of economic losses are magnified in the BTA case. In this scenario, losses for non-coalition members are widespread, ranging from -6% for RUS, -5% for XWS and -3% for CHN. Border tax adjustment have a pronounced impact on relative prices, essential operating as a monopsony markup on exports from the non-coalition states. The terms of trade benefits realized by the coalition states entirely offsets the abatement costs for DEU, EUR, USA and JPN.

From a global perspective, the BTA scenario is inefficient, even when assessed on the basis of a purely utilitarian social welfare metric. (See Figure 11.) Yet, from the perspective of the coalition states, the BTA scenario is a clear winner. Not only are the terms of trade changes beneficial, but this scenario has the net effect of reducing carbon emissions in non-coalition states. The overall leakage rate in the REF scenario is around 15%, and this is reduced to around 7% in the BTA scenario. (See Figure 13.) Hence, if the coalition states were to unilateral reduce emissions to a commensurate degree, their economic costs would be a magnification of the costs observed in the REF scenario.

A logical problem associated with the assessment of border taxes is that coalition states have two motives for imposition of these barriers: leakage and terms-of-trade. As has been argued in Böhringer et al. [2010], it is possible to decompose these motives by performing abatement subject to the constraint imposed by Articles 4.8 and 4.9 of the Kyoto Protocol, articles which require that signatory states compensate developing countries for the impacts of response measures. When faced with compensation, an optimal policy selects solely on the basis of the leakage externality and excludes the "beggar-thy-neighbor" motive which otherwise affects the choice.

We are able to implement this idea in our calculations, producing a quite different distribution of welfare costs, as displayed in Figure 14. In this case, on aggregate, the BTA and EQV scenarios are more costly than the REF scenario, and the EQV scenario is less costly than BTA, although this ranking does not hold for every coalition state.

Leakage rates across fuels and states are displayed in Figure 15. Here we find that CHN and ROW both play an important role in leakage.[5]

Figure 16 provides a sensitivity analysis of model results with respect to the underlying dataset. We find that leakage estimates are highly robust with respect to the disaggregation of commodities. In this case dataset G20IEA has 24 goods, G20IEA has 24 goods, G20EIS has 15 goods and G20SMALL has 7 goods. Each of these models uses the same trade-weighted Armington elasticities, the same elasticities of demand and demand for energy and the same demand structure. Undoubtedly, there exist policy scenarios for which the more disaggregate model produces different results, but in this particular instance, leakage is unaffected.

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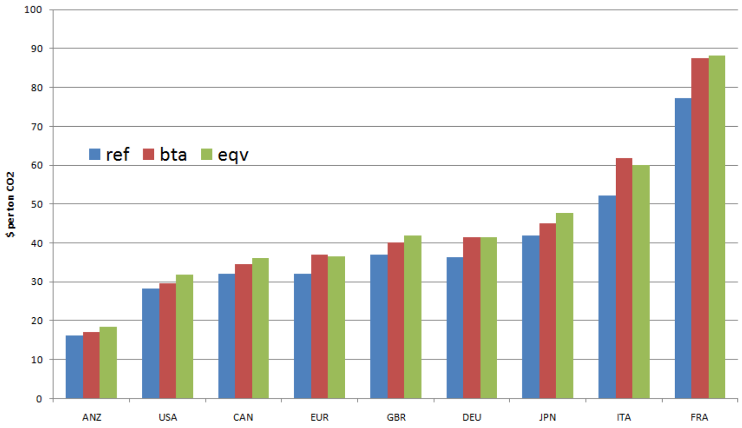
[5] We have assumed that abatement policy in the coalition member states prevents increases in coal exports following the imposition of carbon taxes. If coal were freely exported, the leakage rate can increase to nearly 20%. Limitations on coal export largely explains why leakage is more due to natural gas.

Figure 17 presents a comparison of realized and predicted changes in carbon emissions for the BTA scenario. Realized emissions are those which measured by comparing regional carbon emissions in the REF and BTA scenarios. Border measures reduce trade, and the input-output coefficients would lead one to expect a substantial reduction in emissions. Yet, due to interconnectedness of international trade, emissions embodied in exports to coalition states may be diverted to domestic markets or non-coalition states. In China's case, this diversion is significant – exports to coalition states are reduced but carbon emissions fall by a very small amount.

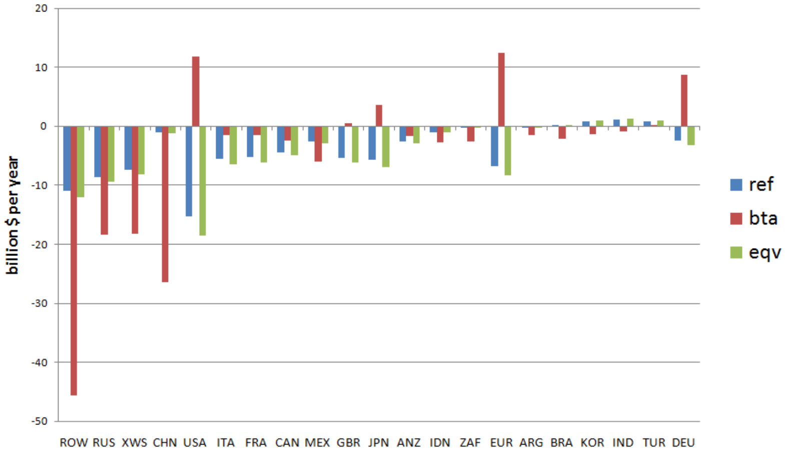
The only non-coalition region for which the yield approaches units is MEX, and its reduction in carbon emissions is due to other factors (e.g., decreases in crude and refined oil exports to USA).

Figure 10: Marginal Cost of Carbon Abatement: 20% Cutback



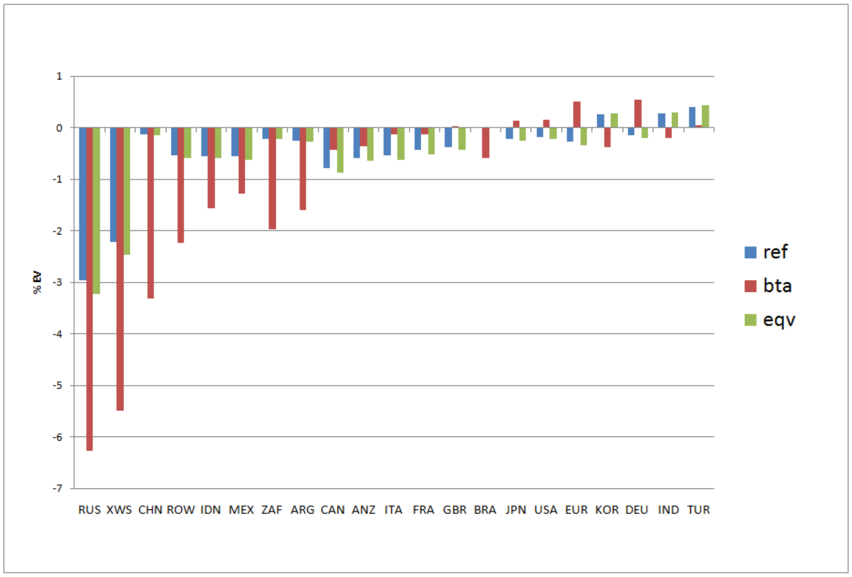
Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 11: Welfare Cost of Mitigation ($)



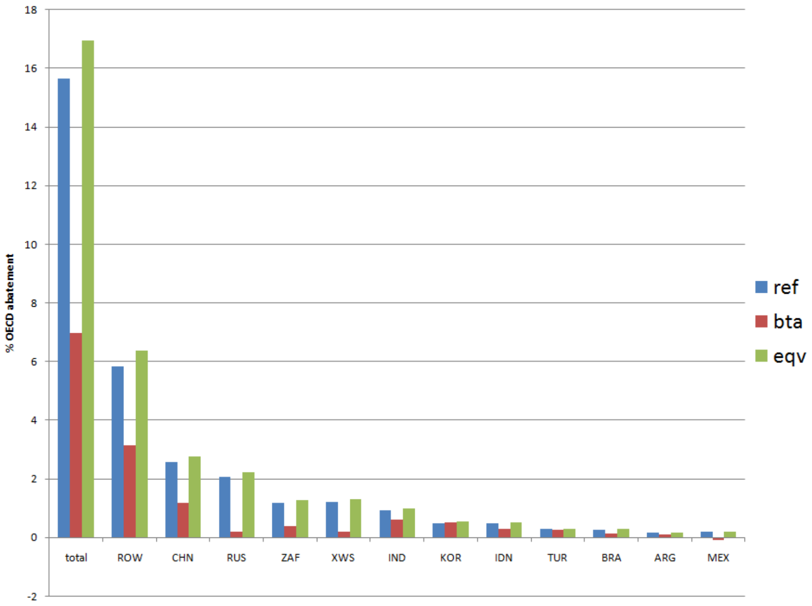
Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 12: Welfare Cost of Mitigation (%)



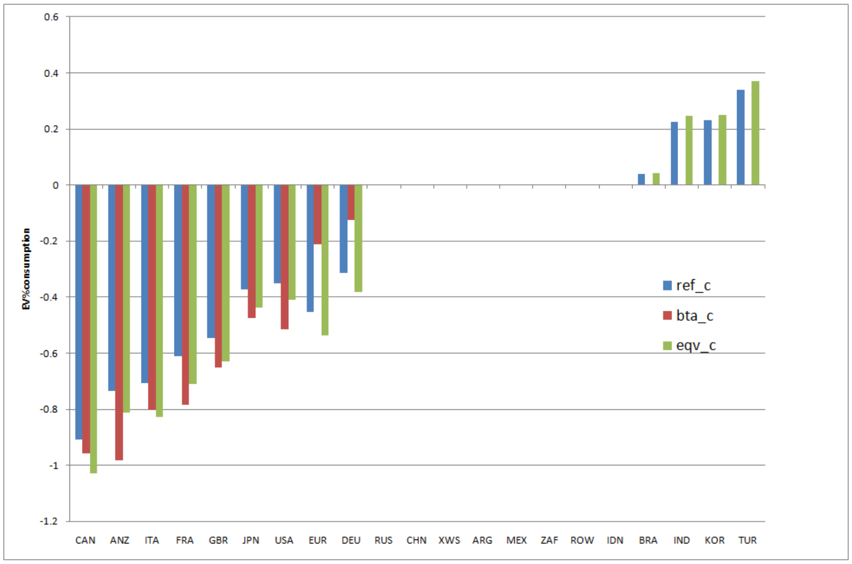
Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 13: Leakage Rates



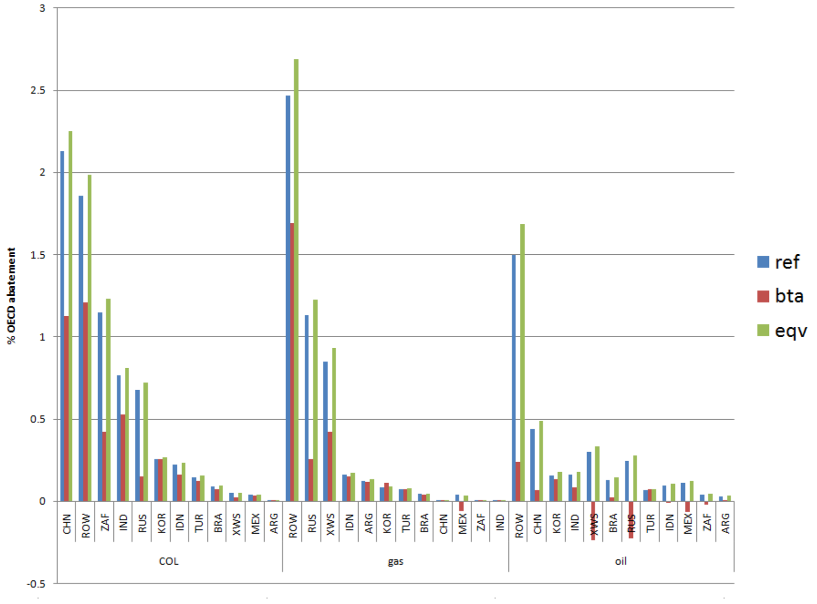
Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 14: Welfare Cost with Endogenous Compensation



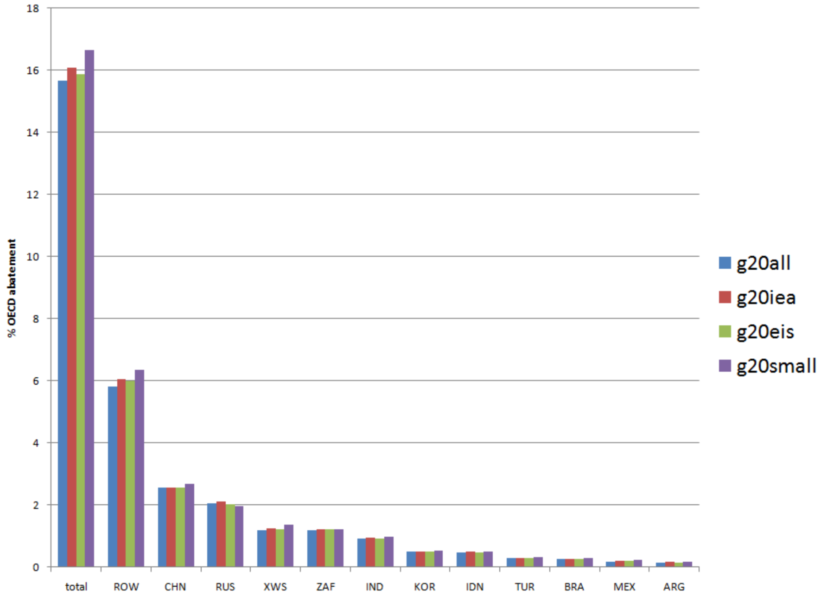
Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 15: Leakage by Fuel and Region



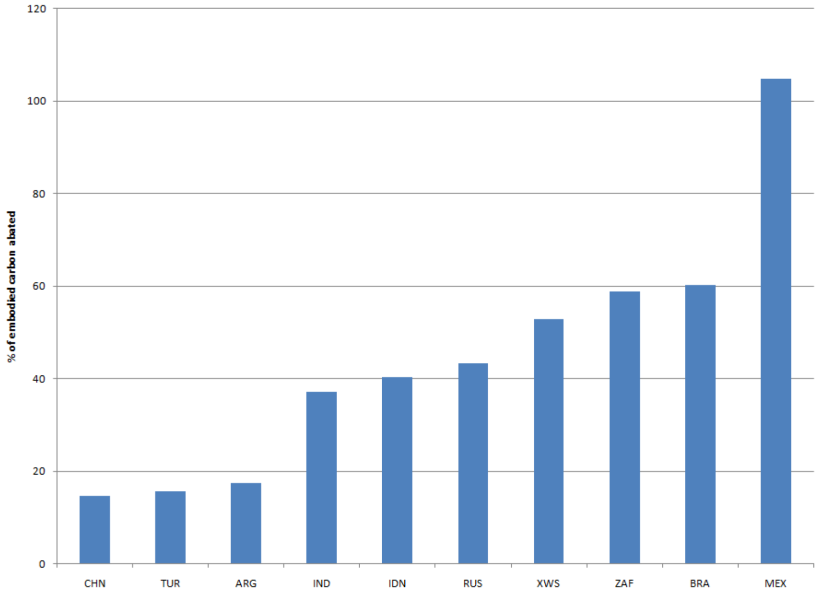
Source: Static GE model based on GTAP 7.1

Figure 16: Leakage Rate in Alternative Aggregations



Source: Static MR-GE calculation with the GTAP 7.1 database.

Figure 17: Effective Yield of Border Measures



Source: Static MR-GE calculation with the GTAP 7.1 database.

5 Conclusions

Carbon leakage describes the extent to which emission-intensive production relocates outside of regulatory borders in response to climate policy. Input-output measures of the carbon content of goods produced in a global economy are interesting but must be used carefully for the purpose of policy assessment.

In a policy analysis framework, the relevant measure of carbon content centers on the marginal impact of the green tariff. Input-output models account for bilateral trade flows but they cannot take into account price elasticities of supply and demand.

Economic equilibrium models can be used to calculate the *carbon yield* of border tax adjustment. In multi-regional trade models with empirically-estimate trade elasticities, carbon yields rarely exceed 60%. For China, the model important contributor to leakage, the carbon yield is on the order of 10%.

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