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Carbon Abatement and International Spillovers

A Decomposition of General Equilibrium Effects

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Abstract. Carbon abatement policies in large open economies affect both the allocation of domestic resources and international market prices. A change in international prices implies an indirect *secondary* burden or benefit for *all* trading countries. Based on simulations with a large-scale computable general equilibrium model of global trade and energy use we show that international spillovers have important welfare implications for carbon abatement policies designed to meet exogenous emission reduction targets. We present a decomposition of the total welfare effect of carbon abatement policies into a primary domestic market effect (at constant international prices) and a secondary international spillover impact as a result of changes in international prices. This decomposition reveals the extent to which domestic abatement costs are increased or decreased as a result of the impact of carbon abatement on international prices.

Key words: applied general equilibrium, carbon abatement, terms of trade

JEL classifications: D58, R13, Q4

1. Introduction

Several OECD countries are considering or have already implemented some kind of carbon tax or quota to comply with emission reduction targets at the national and international level (OECD 2001). Carbon abatement in large open economies not only cause adjustment of domestic production and consumption patterns but also influence international prices via changes in exports and imports. Changes in international prices (*terms-of-trade impacts*) imply a *secondary* benefit or burden which can significantly alter the economic implications of the *primary* domestic policy. Some countries may shift part of their domestic abatement costs to trading partners (*"beggar-thy-neighbor" policies*), while other abating countries face welfare losses from a deterioration of their terms of trade. In the policy debate of climate change, international spillovers from sub-global abatement policies play an important role. The Kyoto Protocol explicitly acknowledges the importance of international spillovers in stipulating that unilateral abatement policies should minimize adverse trade effects on other Parties (UN 1997, Article 2, paragraph 3). Likewise, governments in industrialized countries are concerned that their primary domestic costs of meeting the Kyoto emission reduction targets are magnified through losses in competitiveness as compared to major trading partners which face less stringent abatement targets and may thus benefit from terms-of-trade gains.

There is a broad literature on the potential economic impacts of carbon mitigation both at the single-country and multi-regional levels (for an overview see IPCC 2001). Both strands of literature exhibit shortcomings with respect to the concise analysis of international spillovers. Single- country analyses typically abstract from changes in international prices due to domestic abatement policies, implicitly assuming infinite elastic export supply and import demand of traded goods from the rest of the world. Within multi-region studies, policy impacts are reported as a whole, i.e., no distinction is made between primary effects of domestic action and induced secondary spillovers or feedbacks from international markets.

In this paper, we present a decomposition of the economic effects associated with multilateral carbon abatement policies which breaks down the total policy impact at the single country level into a domestic market effect (i.e. the domestic adjustment holding international prices constant) and international spillovers (i.e. the residual effect accounting for changes in the terms of trade). We apply this method to interpret the economic effects of carbon abatement policies which comply with the emission reduction targets of the Kyoto Protocol. Based on simulations with a large-scale computable general equilibrium model of global trade and energy use, our key insights are as follows:

- Among abating OECD countries, Europe and Japan obtain substantial benefits from international spillovers while the United States, Canada as well as New Zealand and Australia experience negative spillover effects.
- A major determinant for the differences in sign and magnitude of spillovers is the trade position of countries on international crude oil and coal markets. The cutback in global demand for these fossil fuels implies a significant drop of their prices providing economic gains to fossil fuel importers and losses to fossil fuel exporters. These effects explain most of the impacts on developing countries.
- Emissions trading under an agreement like the Kyoto Protocol considerably reduces the magnitude of international spillovers to non-abating regions as compared to unilateral carbon tax policies.
- Non-compliance of the USA with the Kyoto Protocol reduces the positive spillover effects to Europe and Japan as well as the benefits to non-abating developing countries. Canada, New Zealand and Australia, on the other hand, are considerably better off as compared to the scenario where USA fulfills the Kyoto commitment. The main reason is that – without emission constraints for the US economy – global fossil fuel demand decreases less and international prices for coal and crude oil do not fall as much.

The remainder of this paper is organized as follows. Section 2 provides an overview of the model we use for analyzing the economic consequences of global abatement scenarios. Section 3 lays out the decomposition method. Section 4 presents the policy simulations. Section 5 includes a comprehensive sensitivity analysis which

Table I. Overview of sectors and countries/regions

Sectors		Regions	
COL	Coal	CAN	Canada
CRU	Crude oil	CEA	Central European Associates
GAS	Natural gas	EUR	Europe (EU15 and EFTA)
ROP	Refined oil products	FSU	Former Soviet Union (Russian Federation and Ukraine)
ELE	Electricity		
EIS	Energy-intensive sectors	JPN	Japan
Y	Other manufactures and services	OOE	Other OECE (Australia and New Zealand)
CGD	Savings good	USA	United States
		ASI	Other Asia (except for China and India)
		BRA	Brazil
		CHN	China (including Hong Kong and Taiwan)
		IND	India
		MPC	Mexico and OPEC
		ROW	Rest of World

tests the robustness of our results with respect to changes in key assumptions. Section 6 concludes.

2. Analytical Framework and Parameterization

ANALYTICAL FRAMEWORK

This paper is based on simulations with a static 8-sector, 13-region general equilibrium model of the world economy. The sectors in the model have been chosen to distinguish carbon intensive sectors from the rest of the economy to the extent possible given available data. Our model accounts for differences in carbon intensities across countries, the scope for substitutability across carbon-intensive goods, and the potential for terms-of-trade effects triggered by carbon abatement policies. The regional aggregation covers the Annex B parties as well as major non-Annex-B regions that are central to the economic analysis of the Kyoto Protocol. Table I summarizes the 8 sectors and 13 regions incorporated in our model. A detailed algebraic summary of the model is given in Appendix I. The following provides only a sketch of the key features of the model.

Primary factors include labor, capital and fossil-fuel resources. Labor and capital are intersectorally mobile within regions but immobile between regions. Fossil-fuel resources are specific to fossil fuel production sectors in each region.

Production of commodities other than fossil fuels is captured by aggregate production functions which characterize technology through transformation possibilities on the output side and substitution possibilities among inputs. On the output side, production is split between goods produced for the domestic markets and goods produced for the export market, subject to a constant elasticity of transformation (CET). On the input side, needed constant elasticity of substitution (CES) cost functions specify the substitution possibilities between capital, labor, energy and material (non-energy) intermediate inputs. At the top level, non-energy inputs are employed in fixed proportions with an aggregate of energy, capital and labor. The material input of good i in sector j corresponds to a CES Armington aggregate of non-energy inputs from domestic production and imported varieties. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. Finally, at the third level, capital and labor trade off with a constant elasticity of substitution. As to the formation of the energy aggregate, we employ several levels of nesting to represent differences in substitution possibilities between primary fossil fuel types as well as substitution between the primary fossil fuel composite and secondary energy, i.e. electricity.

In the production of fossil fuels, all inputs, except for the sector-specific fossil fuel resource, are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with an exogenously given price elasticity of fossil fuel supply.

Final demand in each region is characterized by utility maximization subject to a budget constraint by a representative agent, holding investment fixed. Total income of the representative household consists of factor income and revenues from taxes levied on output, intermediate inputs, exports and imports, as well as final demand. Final demand of the representative agent is given as a CES composite which combines consumption of a fossil fuel aggregate with a composite of electricity and non-energy consumption goods. Substitution patterns within the latter are reflected via a Cobb-Douglas function. The fossil fuel aggregate in final demand consists of the various fossil fuels trading off at a constant elasticity of substitution. Inputs to final demand, except for crude oil and coal, are specified as an Armington aggregation of imports and the domestic market variety.

All commodities are traded internationally. Crude oil and coal are imported and exported as a homogeneous product, reflecting empirical evidence that these fossil fuel markets are rather integrated due to cheap shipping possibilities (Ellermann 1995). For all other commodities, we adopt the Armington assumption of product differentiation with an explicit representation of bilateral trade flows. The balance of payment constraint, which is warranted through flexible exchange rates, incorporates the benchmark trade deficit or surplus for each region.

PARAMETERIZATION: BASE YEAR CALIBRATION AND FORWARD PROJECTION

The economic effects of carbon abatement policies depend on the extent to which emission reduction targets constrain the respective economies. In other words, the magnitude and distribution of costs associated with the implementation of future emission constraints depend on the baseline (Business-as-Usual – *BaU*) projections for GDP, fuel prices, energy efficiency improvements, etc. In our comparative-static framework, we infer the *BaU* structure of the model regions for the target year (in our case: 2010) using recent projections for economic development. We then measure the costs of abatement relative to that baseline.

As the starting point for our forward projection, we use the GTAP 4 database (McDougall 1997) and OECD/IEA energy statistics (IEA 1996) for 1995. Reconciliation of these data sources (see Babiker and Rutherford 1997) yields the benchmark data to calibrate parameters of the CES functional forms from a given set of quantities and prices (given exogenous elasticities). In a second-step, we do the forward calibration of the 1995 economies to the target year, employing baseline estimates by the US Department of Energy (DOE 1998) for GDP growth, energy demand and future energy prices.

3. Decomposition

The general equilibrium approach is an established analytical framework for evaluating the economic implications of policy intervention in open economies (Shoven and Whalley 1992). Its main virtue is the consistent representation of the direct effects and indirect feedbacks or spillovers induced by exogenous policy changes. However, the interpretation of general equilibrium effects as the total of several partial equilibrium effects is difficult, particularly if the latter work in opposite directions. Therefore, one challenge of general equilibrium modeling is to provide decomposition methods that facilitate the isolated investigation of various partial effects contributing to the total policy impact. In the context of trade policy shocks with respect to changes in the various exogenous policy instruments which account simultaneously for effects on domestic and international markets. For an early approach to the decomposition of general equilibrium impacts, see Miller and Spencer (1977). In the more recent literature (see Huff and Hertel 1997; Harrison, Horridge and Pearson 2000).

Here, we show that the welfare effects of policy intervention in large open economies can be broken down into a *domestic market effect*, assuming that international prices remain constant, and *international spillovers* as a result of changes in international prices (terms-of-trade effect). The key novel idea, formalized below, is that each region of a multi-region model can be represented as a small open economy in order to separate the domestic policy effect under fixed terms of trade. Policy induced changes in international prices from the multi-region model can then be imposed parametrically on the small open economy.

Table II. Summary of notations for the generic MRT

Summary of denotations	
N	Number of commodities (sectors)
K	Number of factors
M	Number of countries/regions
i = 1,. . .,N	Index for commodities (sectors)
j = 1,. . .,N+K	Index for commodities and factors
r,s = 1,. . .,T	Index for region
υ	Revenue function
ω	Cost function
P_{jr}	Price of domestic output good ($j \in \{1, \ldots, N\}$) or factor ($j \in \{N+1, \ldots, N+K\}$) in region r
P^X_{ir}	Export price for good i produced in region r
P^M_{ir}	Price for aggregate import good i imported by region r
P^C_r	Composite price for aggregate household demand in region r
Y_{ir}	Level of production for sector i in region r
M_{ir}	Level of aggregate imports for sector i in region r
C_r	Aggregate household consumption in region r
$\bar{B}_r$	Benchmark trade deficit of surplus of region r (where $\sum_r \bar{B}_r = 0$)
$\bar{E}_{jr}$	Endowment of region r with factor $j (j \in \{N+1, \ldots, N+K\})$

We illustrate the decomposition using a stylized version of the static multi-region trade model introduced in the previous sector omitting any details on the specific functional forms. For each region, two classes of conditions characterize the competitive equilibrium: zero-profit and market clearance. Associated with these conditions are two classes of variables: activity levels and price levels. In equilibrium, each variable is linked to one condition: an activity level is linked to an exhaustion of product constraint, and a commodity price to a market clearance condition. In our algebraic exposition, the notation Π^z_{ir} is used to denote the profit function of sector i in region r, where z is the name assigned to the activity describing domestic production ($z = Y$), aggregate import demand ($z = M$) and final demand ($z = C$).

Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients, which subsequently appear in the market clearance conditions. The notations adopted for our algebraic representation are summarized in Table II. The equilibrium conditions are given in Table III.

We decompose the economic effects associated with policy changes in open economies into a domestic market effect and international spillovers. The domestic market effect reflects a small open economy (SOE) setting where the level of a

Table III. Algebraic summary of the MRT model

Summary of MRT equilibrium conditions	
Zero profit	
Production	$\Pi_{ir}^{Y} = \upsilon(p_{ir}, p_{ir}^{X}) - \omega(p_{1r}, \ldots, p_{(N+K)r}, p_{1r}^{M}, \ldots, p_{Nr}^{M})$
Aggregate import demand	$\Pi_{ir}^{M} = p_{ir}^{M} - \omega(p_{i1}^{X}, \ldots, p_{iT}^{X})$
Final demand	$\Pi_{r}^{C} = p_{r}^{C} - \omega(p_{1r}, \ldots, p_{Nr}, p_{1r}^{M}, \ldots, p_{nr}^{M})$
Market clearance	
Factor markets	$\bar{E}_{jr} = \sum_{i=1}^{N} Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_j}$
Domestic good markets	$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}} = \sum_{j=1}^{N} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}} + C_r \frac{\partial \Pi_{r}^{C}}{\partial p_{ir}}$
Export good markets	$Y_{ir} \frac{\partial \Pi_{ir}^{Y}}{\partial p_{ir}^{X}} = \sum_{s=1}^{T} M_{is} \frac{\partial \Pi_{is}^{Y}}{\partial p_{ir}^{X}}$
Import composite markets	$M_{ir} = \sum_{j=1}^{N} Y_{jr} \frac{\partial \Pi_{jr}^{Y}}{\partial p_{ir}^{M}} + C_r \frac{\partial \Pi_{r}^{C}}{\partial p_{ir}^{M}}$
Aggregate consumption market	$C_r = (\bar{B}_r + \sum_{j=N+1}^{N+K} p_{jr} \bar{E}_{jr}) / p_{r}^{C}$

region's imports and exports have no effect on the terms of trade. Algebraically, the SOE specification is identical to the MRT model formulation with the sole difference that prices on international markets are fixed in international currency units, i.e. the world market price of commodity i from region r is exogenously given as $\bar{P}_{ir}^{X}$. Foreign closure of the SOE model requires an additional condition that states equality of the value of imports with the value of exports (after accounting for some exogenous balance of payment deficit or surplus in the benchmark). Table IV provides the algebraic summary of the SOE submodel for each region of the MRT model.

The SOE specification of the MRT regions allows us to impose changes in international prices (terms of trade) parametrically by altering the values for $\bar{p}_{ir}^{X}$. Hence, we can easily check the consistency of our decomposition for any MRT policy simulation (counterfactual equilibrium). We fix international prices $\bar{p}_{ir}^{X}$ from the SOE perspective at the level p_{ir}^{X}, which is determined endogenously by the MRT counterfactual, and then initialize all level values for the SOE variables with the MRT solution value for the respective region. Without numerical work, we should be able to replicate the MRT solution for any region from an SOE perspective. Having passed this consistency check, we can use the SOE framework in order to decompose the total policy effect into a domestic market effect and an international spillovers. Computation of the domestic market effect simply requires that we keep the international prices at the benchmark (reference) level and then impose the domestic policy change on the specific country. By definition, the domestic market effect must be zero for any country where no domestic policy change applies.

Table IV. Algebraic summary of the SOE model

Summary of SOE equilibrium conditions ($\forall r \in \{1, \ldots, T\}$)	
Zero profit	
Production	$\Pi_i^Y = \upsilon(p_i \bar{p}_i^X) - \omega(p_1, \ldots, p_{(N+K)}, p_1^M, \ldots, p_N^M)$
Aggregate import demand	$\Pi_i^M = p_i^M - \omega(\bar{p}_{i1}^X, \ldots, \bar{p}_{iT}^X)$
Final demand	$\Pi^C = p^C - \omega(p_1, \ldots, p_N, p_1^M, \ldots, p_N^M)$
Market clearance	
Factor markets	$\bar{E}_j = \sum_{i=1}^N Y_i \frac{\partial \Pi_i^Y}{\partial p_j}$
Domestic good markets	$Y_i \frac{\partial \Pi_i^Y}{\partial p_i} = \sum_{j=1}^N Y_j \frac{\partial \Pi_j^Y}{\partial p_i} + C \frac{\partial \Pi^C}{\partial p_i}$
Import composite markets	$M_i = \sum_{j=1}^N Y_j \frac{\partial \Pi_j^Y}{\partial p_i^M} + C \frac{\partial \Pi^C}{\partial p_i^M}$
Aggregate consumption market	$C = (\sum_{j=N+1}^{N+K} p_j \bar{E}_j + \bar{B}) / p^C$
Foreign closure (BOP)	$\sum_{i=1}^N Y_i \frac{\partial \Pi_i^Y}{\partial \bar{p}_i^X} \bar{p}_i^X = \sum_{i=1}^N \quad \sum_{s=1}^T Y_{ir} \frac{\partial \Pi_i^M}{\partial \bar{p}_{is}^X} \bar{p}_{is}^X + \bar{B}$

Obviously, the international spillovers are equal to the difference between the total (general equilibrium) policy effect and the domestic market effect.

Our decomposition allows measuring of the international spillovers by commodity. We can simply parameterize the SOE model with the international price for the respective commodity using the MRT counterfactual solution while keeping the international prices for the other commodities at the benchmark level.

4. Decomposing Welfare Effects of the Kyoto Protocol

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UN 1997) foresees greenhouse gas emission constraints for Annex B parties which include industrialized countries and countries in transition. On average, Annex B parties have committed themselves to reducing greenhouse gas emissions by 5.2% from 1990 levels in the budget period 2008 to 2012. The developing countries have so far refused any abatement commitment. The reason for this is that they fear negative effects of emissions limitation on their economic development and demand primary action by the developed world with large historical and current emissions.

Our comparative-static model measures the costs of implementing Kyoto as compared to the Business-as-Usual (*BaU*) reference point in 2010 without any emission constraint. Welfare implications are reported as percentage change in Hicksian equivalent variation (%HEV) of income from *BaU*. In the simulations reported below we distinguish two scenarios: The scenario *NTR* refers to a situation where Annex B countries apply domestic carbon taxes which are high enough

Table V. Emission abatement requirements and marginal abatement costs

Region	% Reduction with respect to 1990	% Reduction with respect to 2010	Marginal abatement cost (*NTR*)*	Marginal abatement cost (*TRD*)*
CAN	6	28	230	46
CEA	7	–6	1	46
EUR	8	14	107	46
FSU	0	–48	—	46
JPN	6	26	300	46
OOE	–7	16	76	46
USA	7	27	160	46

*in $1995 US/metric ton of carbon

to meet their individual Kyoto commitments; the scenario *TRD* allows emission trading among Annex B countries implying that marginal abatement costs are equalized across this group of countries. In both scenarios, revenues from carbon taxation or carbon permit sales are recycled lump-sum to the representative agent in each region.

EMISSION REDUCTION REQUIREMENTS AND MARGINAL ABATEMENT COSTS

It is important to note that the effective emission constraint for Annex B countries under the Kyoto Protocol must be measured against the *BaU* economic activity without abatement requirements. Because emissions of most Annex B countries grow significantly along the baseline as compared to 1990 levels, the Kyoto targets which are stated with respect to 1990 translate into much higher effective carbon reduction requirements with respect to *BaU* emission levels in 2010. For example, OOE is allowed to *increase* emissions under the Kyoto Protocol by 7% over 1990 levels, while it effectively faces the need for a *decrease* of 16% from *BaU* emissions in 2010. The two outliers are CEA and, in particular, FSU, whose projected emission levels for 2010 are below 1990 levels, due to economic recession and industrial restructuring that took place between 1990 and 2000.

Table V presents the Kyoto reduction targets with respect to 1990 emission levels as well as the effective percentage cutbacks with respect to *BaU* emission levels in 2010. In addition, the marginal abatement costs for the cases *NTR* and *TRD* are listed. We see that there are large differences in the marginal abatement costs for the *NTR* case which indicates the opportunity for substantial overall efficiency gains from emission trading.

The variation in marginal abatement costs for the *NTR* case stem to some extent from the differences in relative cutback requirements across countries. The further out we are on the abatement cost curve, the more costly it gets at the margin to substitute away from carbon in production and consumption. Other key determinants of marginal abatement costs for the *NTR* case include *BaU* energy price levels and carbon intensities. A country with higher *BaU* energy prices require larger carbon taxes to achieve the same percentage emission reduction than countries with lower *BaU* energy prices. Likewise, countries which are carbon-intensive in production sectors where inter-fuel substitution comes is less costly (e.g. the electricity sector) require relatively lower carbon taxes to achieve substantial emission reductions. These relationships explain, for examples, why JPN faces higher carbon taxes compared to USA or CAN. Although its percentage reduction target is smaller, *BaU* energy prices in JPN are considerably higher than in USA and CAN. JPN has little scope for cheap inter-fuel substitution in the generation of electricity which is largely nuclear-power based. As a consequence, JPN has to cut back relatively more emissions in other sectors where abatement comes more costly at the margin.

As an aside, note that CEA has to impose a very low carbon tax in order to comply with the Kyoto Protocol, although baseline projections indicate at first glance that its Kyoto target is not restrictive. The reason for this is that, under the Kyoto Protocol, CEA gains a comparative advantage in the production of energy-intensive goods as compared to mitigating OECD countries, which would increase domestic emissions over the Kyoto target if CEA did not issue emissions permits or levy a carbon tax.

WELFARE DECOMPOSITION FOR DOMESTIC CARBON TAXES (NTR)

The total general equilibrium welfare effects emerging from regional carbon taxes under the Kyoto protocol are reported as *Total Policy Effect* in Table VI. We see that the tax-induced reallocation of resources, such as fuel shifting or energy savings, causes substantial adjustment costs for OECD countries. Furthermore, there are considerable international spillover effects from abating industrialized countries to non-abating countries: Adjustments on international markets induce welfare losses for FSU as well as MPC and, to a much smaller extent, for ROW; all other non-abating countries benefit to varying degrees from the changes in international prices associated with carbon abatement in OECD countries.

To gain insights into the different sources of welfare changes across regions, we make use of our decomposition method. Table VI summarizes how the domestic market is modified to produce the total policy effect as we successively impose changes in international prices determined by the MRT model within the SOE models. The final column of Table VI indicates the relative magnitude of international spillovers measured in percent of the total policy effect. Obviously, the international spillovers must be identical to the total policy effect for those countries which do not undertake domestic abatement, i.e. countries whose domestic market effect is zero. As to abating countries, our decomposition provides information on the sign and relative magnitude of the primary domestic and the secondary

Table VI. Welfare decomposition for carbon tax case (*NTR*)

	Domestic Market Effect (in % HEV)	Fossil Fuel Market Effect** (in % HEV)	Total Policy Effect (in % HEV)	International Spillovers* (in % of Total Policy Effect)
CAN	–0.69	–0.86	–0.88	21
CEA	0.00	0.26	0.29	100
EUR	–0.14	–0.06	–0.06	-116
FSU	0.00	–0.43	-1.03	100
JPN	–0.44	–0.38	–0.30	–47
OOE	–0.13	–0.47	–0.65	81
USA	–0.36	–0.38	–0.40	9
ASI	0.00	0.26	0.14	100
BRA	0.00	0.08	0.09	100
CHN	0.00	0.26	0.20	100
IND	0.00	0.32	0.27	100
MPC	0.00	–0.77	–0.99	100
ROW	0.00	–0.05	–0.08	100

*Calculated as: 100 * [(Total Policy Effect) – (Domestic Market Effect)] / (Total Policy Effect)
**Welfare change accounting for domestic market effect and international price changes for crude oil and coal.

international impacts. International spillovers are negative for USA, CAN and OOE, whereas CEA, EUR, and JPN benefit from the adjustments on international markets.

Abstracting from induced changes in international prices, binding emission constraints imply adjustment costs for all OECD countries that are correlated to the level of the required abatement as well as to the *BaU* energy intensities of the respective regions. Regarding international spillovers, most important are the adjustments on international coal and crude oil markets (see column *Fossil Fuel Market Effect* to Table VI). The cutback in demands for fossil fuels from abating OECD countries depresses the international prices for oil and coal. As a consequence, countries which are net importers of coal and crude oil gain, whereas net exporting countries lose. Table VII provides a summary of the *BaU* net trade position in coal and crude oil across countries. For CAN, MPC, and ROW, which are net exporters of both coal and crude oil, the aggregate welfare effect is unambiguously negative. Likewise, net importers EUR, JPN, CHN, IND, BRA and ASI experience welfare gains. For countries which are net importer of one fossil fuel *and* net exporter of the other, the aggregate effect depends on export and import quantities as well as the relative changes in international coal and crude oil prices.

Table VII. Net trade position on global coal and crude oil markets (*BaU* 2010)

	CAN	CEA	FSU	EUR	JPN	OOE	USA	ASI	CHN	BRA	IND	MPC	ROW
Coal	E	E	I	I	I	E	E	I	I	I	I	E	E
Crude oil	E	I	E	I	I	I	I	I	I	I	I	E	E

*E: Exporter, I: Importer

FSU, for example, loses more on the crude oil export side than it benefits through lower prices for coal imports.

In the next step, we account for international price changes in non-energy markets where traded goods are differentiated by region of origin. On these markets, developing countries typically face adverse spillover effects. Apart from higher export prices of developed countries, developing countries suffer from a scale effect as economic activity and hence import demand by developed countries decline. On the other hand, this effect can be (partially) offset by an opposite substitution effect. Developing countries gain market shares in Annex B countries because their exports become more competitive. The same mechanisms apply to trade between abating countries with large differences in imposed carbon taxes. As an example, OOE, which has low carbon taxes, suffers from increased export prices of trading partners with high carbon taxes, such as Japan.

WELFARE DECOMPOSITION FOR EMISSION TRADING (TRD)

We now turn to the decomposition of welfare effects when Annex B countries can trade emissions. As compared to purely domestic abatement, the possibility of export or importing carbon rights at an uniform international permit price provides substantial benefits to all countries involved in carbon trading (see column *Carbon Trade Effects* of Table VIII). Annex-B countries CAN, EUR, JPN, OOE and USA, whose marginal abatement costs under *NTR* are above the equalized *TRD* marginal abatement costs, import carbon rights and reduce their domestic adjustment cost. On the other hand, Annex B countries CEA and FSU, who do not abate initially, export carbon rights and *improve* welfare relative to baseline levels. Note that there are two sources for overall welfare gains: (i) efficiency increases from the equalization of marginal abatement costs, and (ii) an implicit relaxation of the carbon emission constraint for Annex-B countries due to the supply of initially unused carbon rights from FUS. Under *TRD*, FSU, whose baseline emissions are far below its Kyoto entitlements, sells larger amounts of carbon rights which it did not use in the *NTR* case – a phenomenon referred to as *Hot Air* (see e.g. Böhringer 2000). This explains the high welfare gains for FSU.

The remaining international spillovers from energy and non-energy markets have the same qualitative welfare implications and economic interpretation as in the proceeding section for the *NTR* scenario. However, emission trading under

Table VIII. Welfare decomposition for tradable permit case (*TRD*)

	Domestic Market Effect (in % HEV)	Carbon Trade Effect (in % HEV)	Total Policy Effect (in % HEV)	International Spillovers* (in % of Total Policy Effect)
CAN	–0.69	–0.30	–0.45	-54
CEA	0.00	0.42	0.56	100
EUR	–0.14	–0.10	–0.04	-274
FSU	0.00	4.59	4.01	100
JPN	–0.44	–0.12	–0.05	–767
OOE	–0.13	–0.12	–0.38	67
USA	–0.36	–0.21	–0.21	–73
ASI	0.00	0.00	0.08	100
BRA	0.00	0.00	0.04	100
CHN	0.00	0.00	0.07	100
IND	0.00	0.00	0.11	100
MPC	0.00	0.00	–0.46	100
ROW	0.00	0.00	–0.05	100

*Calculated as: 100 * [(Total Policy Effect) – (Domestic Market Effect)] / (Total Policy Effect)

the Kyoto Protocol significantly reduces international spillovers to non-abating countries in comparison to the *NTR* scenario.

5. Sensitivity Analysis

The preceding section provided a detailed assessment of the spillover effects under central case assumptions. We have performed a detailed sensitivity analysis of the central case with respect to changes in five key assumptions: oil price responsiveness, ease of substitution among traded non-energy goods, capital mobility, the marginal costs of public funds, and (non-) compliance of the USA to the Kyoto Protocol. Details of these calculations are provided in Appendix II. In this section we summarize changes the quantitative impacts as compared to the *NTR* reference case (*ref*). While the magnitude of our results can be altered as a result of model assumptions, we have found that most of the qualitative insights regarding the determinants of international spillovers reported for the reference case remain robust.

RESPONSIVENESS OF CRUDE OIL PRICES

The supply elasticity for crude oil determines how its price responds to changes in the demand for crude oil. In the reference case, the crude oil supply elasticity is set to 1.0. In our sensitivity analysis we double this value for the high elasticity case (*high*) and halve it for the low elasticity case (*low*). Lower elasticities imply that the crude oil price is more responsive to a change in the demand. Therefore, when the OECD reduces its demand for crude oil, the price drops more for lower elasticity values than for higher values. Increasing the price response causes oil exporting nations to suffer more when a carbon abatement policy is enacted. Conversely, higher price responses lead to greater benefits for oil importing countries. On international crude oil markets exporting regions CAN, FSU, MPC and ROW face smaller welfare losses for higher supply elasticities because the drop in the world market price for crude oil becomes less pronounced. On the contrary, crude oil importing regions benefit less from the crude oil market spillovers.

Changes in supply elasticities do not matter from a SOE perspective where international prices are fixed: The domestic market effect for abating OECD countries remains unchanged. In the MRT perspective, an increase in the supply elasticity reduces overall terms-of-trade gains (EUR, JPN) or increase overall terms-of-trade losses (USA, OOE) for crude oil importing OECD countries; CAN as the only crude oil exporter among OECD reduces its overall terms-of-trade losses towards higher supply elasticities. The implications of changes in coal supply elasticities are similar to what we have found for crude oil.

TRADE ELASTICITIES FOR NON-ENERGY GOODS

Aside from crude oil and coal, imported and domestically produced goods are treated as imperfect substitutes in both the MRT and SOE models. For each product variety the substitution possibility between the domestically produced good and the import aggregate from other regions is characterized by a constant elasticity of substitution. This elasticity measures how easily imports can substitute for domestically produced goods. In our policy simulations the trade elasticity affects, for example, the extent to which OECD's domestically produced goods is displaced by non-OECD imports when a carbon abatement policy raises the cost of OECD produced goods. In the reference case (*ref*), the elasticity of substitution between the domestic good and the import aggregate is set equal to 4.0, and the elasticity of imports from different regions within the import aggregate is set equal to 8.0. In the sensitivity analysis, we either halve (*low* case) or double (*high* case) these values.

In the absence of terms-of-trade effects, the cost of carbon abatement moves inversely with trade elasticities because when domestic and imported goods are closer substitutes countries can more easily substitute away from carbon-intensive inputs into production and consumption. Depending on a country's initial trade structure, international spillovers may strengthen, weaken or even outweigh the unambiguous domestic policy effect associated with a change in trade elasticities. This is because the trade elasticity determines the extent to which domestic taxes can be passed further to trading partners. With lower elasticities, a country importing carbon-intensive goods from a trading partner with high domestic carbon taxes is less able to substitute away from the more expensive imports to the cheaper domestically produced goods.

Our sensitivity analysis reveals that among OECD countries the USA, EUR and JPN are worse off for higher trade elasticities indicating their reduced scope for effective tax burden shifting. On the other hand, developing regions such as CHN, MPC and ROW have more beneficial spillover impacts with higher elasticities because (i) they can more readily substitute away from more expensive energy-intensive OECD goods, and (ii) they can take greater advantage of their lower domestic production costs in competing against the OECD.

CAPITAL MOBILITY

In the reference case (*ref*), capital is intersectorally mobile but immobile across domestic borders. When we allow for global capital mobility (*gkm*), the welfare-decreasing domestic policy effect for abating countries becomes more pronounced. Carbon taxes reduce the energy use in production which drives down factor productivity. Capital owners in abating countries can avoid the implied fall in capital return by moving capital to the international capital market where its earns the higher *BaU* international interest rate. However, capital flight further decreases the productivity of the remaining factors labor and fossil-fuel resources which, in total, increases the tax-induced distortions and the loss in real income as compared to the reference case.

Capital mobility reduces the magnitude of positive international spillovers to non-abating countries. The main reason is that capital inflows reduce the comparative advantage of these countries in the production of energy-intensive goods. At the global level, capital mobility decreases the world-wide cost of complying with the Kyoto targets because the size the global production possibility frontier is moved outwards.

REVENUE RECYCLING

It is well-known that the way revenue from carbon taxes (or auctioned tradable permits) are used has major impacts on the social costs of the climate policy (see e.g. Pearce 1991; Goulder 1995; Bovenberg 1999). When revenues are used to reduce existing tax distortions, carbon taxes present an opportunity to simultaneously improve environmental quality and offset at least part of the welfare losses of climate policies by reducing the costs of the tax system. The starting point of this double dividend debate is how expensive it is to raise government income, i.e., how big are marginal costs of public funds (MCF). A MCF of 15%, for example, indicates an economy-wide cost of 1.15 dollar for raising 1 dollar tax revenues. A high MCF gives more scope for a double dividend than a small MCF because revenue-neutral cutbacks of highly distortionary taxes promise larger efficiency gains.

In our reference case, the revenues of carbon taxes are recycled lump-sum to the representative agent in each region. We therefore do not capture the welfare effects of swapping carbon taxes for distortionary existing taxes. The reason for this approach is straightforward: By necessity, global models are much higher aggregated in their treatment of specific issues. In order to represent regional interactions and spillovers at the global level, local details which may differ largely from country to country – such as the tax system of labor market imperfections – must be sacrificed. Here, we address the issue of revenue recycling in a stylized way to illustrate its importance for the total costs of carbon abatement. We adopt uniform estimates for the MCFs across regions and calculate to what extent revenues from carbon taxes in abating countries reduce the welfare costs of carbon emission constraints. As a simple shortcut, we multiply the carbon tax revenue with the MCF and place the resulting amount to the credit of the representative agent in the respective region.

In our sensitivity analysis we study the implications of revenue recycling for cases where MCFs in Annex B equal 0% (ref), 10% and 25%. With MCFs greater than zero we find the domestic policy impacts are substantially reduced. For an MCF of 25%, carbon tax policies may even net gross welfare gains. Positive MCFs result in smaller indirect positive feedbacks to non-abating countries. The latter benefit from reduced OECD income losses or even income gains via higher export demands of OECD countries.

NON-COMPLIANCE OF THE USA

The United States have stated repeatedly that they will not ratify the Kyoto Protocol in its present form. In March 2001, the US government *de facto* withdrew from the Protocol. We have therefore considered a scenario in which the USA does not accept any emission constraint on its economy whereas all other ANNEX-B countries still stick to their Kyoto commitments. Non-compliance of the USA implies zero domestic adjustment costs for the US economy whereas the domestic policy effects of all other abating Annex-B countries remain unchanged as compared to the reference case. Without emission constraints for the US economy, positive spillover effects to Europe and Japan and many of the non-abating developing countries are considerably reduced. Canada, New Zealand and Australia, on the other hand, are better off. The main reason for these effects is that global fossil fuel demand decreases less and therefore international prices for coal and crude oil do not fall as much. Of course, non-compliance of the USA implies higher global carbon emissions than in the reference case. It should be noted that non-compliance of the USA has a negative impact on the global environmental effectiveness of abatement in the remaining Annex-B countries. Without domestic emission constraints, USA becomes more competitive in the production of energy-intensive goods as compared to the reference case. This induces an increase of the US emissions beyond *BaU* levels. The carbon leakage rate for the USA amounts to 13 % which means that for every 10 tons of carbon abated in the other Annex- B countries the USA increases its emissions by 1.3 tons.

6. Conclusions

In this paper, we highlighted the importance of international spillovers for the welfare implications induced by alternative carbon abatement policies under the Kyoto Protocol. In order to gain insights into how international markets transmit policy impacts between countries we developed a decomposition technique that isolates international spillovers. The decomposition reveals that, among the Kyoto signatory countries, Australia, Canada, New Zealand and USA bear a secondary burden through changes in international terms of trade, whereas Europe and Japan experience secondary benefits. Most developing countries gain a comparative advantage due to abatement in Annex B regions, but fossil fuel exporters such as Mexico and OPEC are seriously hurt. A major determinant for the differences in sign and magnitude of spillovers is the trade position of countries on international coal and crude oil markets: Depressed international prices for fossil fuels, that are due to the cutback in global fossil energy demand, provide gains for fossil fuel importers and losses for fossil fuel exporters. The latter mechanism also explains why non-compliance of the USA with the Kyoto Protocol (i.e. smaller cutbacks in global fossil fuel demand) reduces positive international spillovers to fuel-importing regions and weakens negative spillovers to fossil fuel exporters.

Emission trading considerably reduces the magnitude of spillovers under the Kyoto Protocol to non-abating countries as compared to unilateral carbon tax policies. In addition to the standard efficiency reasoning, this finding may provide an additional argument in the policy debate in favor of international permit trading.

Beyond the current application on climate policy analysis, it should be noted that our decomposition represents a general concept and is intuitively appealing. Furthermore, its numerical implementation within a multi-regional general equilibrium framework is straightforward which suggests its application to other fields of policy intervention.

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Appendix I: Algebraic Model Summary

This appendix provides an algebraic summary of the equilibrium conditions for our comparative-static model designed to investigate the economic implications of the Kyoto Protocol in 2010 as compared to a Business-as-Usual economic development in which no carbon abatement policies apply. Before presenting the algebraic exposition we state our main assumptions and introduce the notation.

- Nested separable constant elasticity of substitution (CES) functions characterize the use of inputs in production. All production exhibits non-increasing returns to scale. Goods are produced with *c*aptial, *l*abor, *e*nergy and *m*aterial (KLEM).
- A representative agent (RA) in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labor and capital. The RA maximizes utility from consumption of a CES composite subject to a budget constraint with fixed investment demand (i.e. fixed demand for the savings good). The aggregate consumption bundle combines demands for fossil fuels, electricity and non-energy commodities. Total income of the RA consists of factor income and taxes (including carbon tax revenues).
- Supplies of labor, capital and fossil-fuel resources are exogenous. Labor and capital are mobile within domestic borders but cannot move between regions; natural resources are sector specific.
- All goods, except for coal and crude oil, are differentiated by region of origin. Constant elasticity of transformation functions (CET) characterize the differentiation of production between production for the domestic markets and the export markets. Regarding imports, nested CES functions characterize the choice between imported and domestic varieties of the same good (Armington). Crude oil and coal are imported and exported as homogeneous products.

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_{ir}^{z} is used to denote the profit function of sector j in region r where z is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients (Shepard's lemma), which appear subsequently in the market clearance conditions. We use i (aliased with j) as an index for commodities (sectors) and r (aliased with s) as an index for regions. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. Tables I.1–I.6 explain the notations for variables and parameters employed within our algebraic exposition. Figures A.1–A.4 provide a graphical exposition of the production and final consumption structure.

II.1. ZERO PROFIT CONDITIONS

1. Production of goods except fossil fuels:

$$\Pi_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{KLE}\left[\theta_{ir}^{E} p_{ir}^{E^{1-\sigma_{KLE}}} + (1-\theta_{ir}^{E})\left(w_r^{\alpha_{jr}^{L}} v_r^{\alpha_{jr}^{K}}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \quad i \notin FF$$

2. Production of fossil fuels:

$$\Pi_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_{ir}^{Q} q_{jr}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q})\left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v^{r} + \sum_{j} \theta_{jir}^{FF} p_{jr}^{A}\right)^{1-\sigma_{Q,i}}\right]^{\frac{1}{1-\sigma_{Q,i}}} = 0$$

$i \in FF$

3. Sector-specific energy aggregate:

$$\Pi_{ir}^{E} = p_{ir}^{E} - \left\{\theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1-\theta_{ir}^{ELE}) \left[\theta_{ir}^{COA} p_{\{COA,r\}}^{A^{1-\sigma_{COA}}} + (1-\theta_{ir}^{COA})\left(\Pi_{j \in LQ} p_{jr}^{A^{\beta_{jir}}}\right)^{1-\sigma_{COA}}\right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}}\right\}^{\frac{1}{1-\sigma_{ELE}}} = 0$$

4. Armington aggregate:

$$\Pi_{ir}^{A} = p_{ir}^{A} - \left[(\theta_{ir}^{A} p_{ir}^{1-\sigma_A} + (1-\theta_{ir}^{A}) p_{ir}^{M^{1-\sigma_A}})^{\frac{1}{1-\sigma_A}} + t_r^{CO2} a_i^{CO2}\right] = 0$$

5. Aggregate imports across import regions:

$$\Pi_{ir}^{M} = p_{ir}^{M} - \left(\sum_{s} \theta_{isr}^{M} p_{is}^{X^{1-\sigma_M}}\right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

$$\Pi_{r}^{C} = p_{r}^{C} - \left(\theta_{Cr}^{E} p_{Cr}^{E^{1-\sigma_{EC}}} + (1-\theta_{Cr}^{E})\left[\Pi_{i \notin FF} p_{ir}^{A^{\gamma_{ir}}}\right]^{1-\sigma_{EC}}\right)^{\frac{1}{1-\sigma_{EC}}} = 0$$

7. Household energy demand:

$$\Pi_{Cr}^{E} = p_{Cr}^{E} - \left[\sum_{i \in FF} \theta_{iCr}^{E} p_{ir}^{A^{1-\sigma_{FF,C}}}\right]^{\frac{1}{1-\sigma_{FF,C}}} = 0$$

II.2. MARKET CLEARANCE CONDITIONS

8. Labor:

$$\bar{L}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r}$$

9. Capital:

$$\bar{K}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$$

10. Natural resources:

$$\bar{Q}_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} \quad i \in FF$$

11. Output for domestic markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} = \sum_j A_{jr} \frac{\partial \Pi_{ir}^A}{\partial p_{ir}}$$

12. Output for export markets:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^X} = \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}^X}$$

13. Sector specific energy aggregate:

$$E_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$$

14. Import aggregate:

$$M_{ir} = A_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^M}$$

15. Armington aggregate:

$$A_{ir} = \sum_j Y_{jr} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{ir}^A}$$

16. Household consumption:

$$C_r p_r^C = w_r \bar{L}_r + v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} + t_r^{CO2} \overline{CO2}_r + p_{CGD,r} \bar{Y}_{CGD,r} + \bar{B}_r$$

17. Aggregate household energy consumption:

$$E_{Cr} = Cr \frac{\partial \Pi_r^C}{\partial p_{Cr}^E}$$

18. Carbon emissions:

$$\overline{CO2}_r = \sum_i A_{ir} a_i^{CO2}$$

Table I.1 Sets

i	Sectors and goods
j	Aliased with i
r	Regions
s	Aliased with r
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

Table I.2 Activity variables

Y_{ir}	Production in section *i* and region *r*
E_{ir}	Aggregate energy input in sector *i* and region *r*
M_{ir}	Aggregate imports of good *i* and region *r*
A_{dir}	Armington aggregate for demand category *d* of good *i* in region *r*
C_r	Aggregate household consumption in region *r*
E_{Cr}	Aggregate household energy consumption in region *r*

Table I.3 Price variables

P_{ir}	Output price of good *i* produced in region *r* for domestic market
P_{ir}^X	Output price of good *i* produced in region *r* for export market
P_{ir}^E	Price of aggregate energy in sector *i* and region *r*
P_{ir}^M	Import price aggregate for good *i* imported to region *r*
P_{ir}^A	Price of Armington good *i* in region *r*
P_r^C	Price of aggregate household consumption in region *r*
P_{Cr}^E	Price of aggregate household energy consumption in region *r*
w_r	Wage rate in region *r*
v_r	Price of capital services in region *r*
q_{ir}	Rent to natural resources in region *r* ($i \in FF$)
t_r^{CO2}	CO_2 tax in region *r*

Table I.4 Cost shares

θ_{ir}^{X}	Share of exports in sector i and region r
θ_{jir}	Share of intermediate good j and sector i and region r (i $\notin$ FF)
θ_{ir}^{KLE}	Share of KLE aggregate in sector i and region r (i $\notin$ FF)
θ_{ir}^{E}	Share of in the KLE aggregate of sector i and region r (i $\notin$ FF)
α_{ir}^{T}	Share of labor ($T = L$) or capital (T=K) in sector i and region r (i $\notin$ FF)
θ_{ir}^{Q}	Share of natural resources in sector i and region r (i $\notin$ FF)
θ_{Tir}^{FF}	Share of good i ($T = i$) or labor ($T = L$) or capital ($T = K$) in sector i and region r (i $\notin$ FF)
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector i and region r (i $\notin$ FF)
θ_{ir}^{ELE}	Share of electricity in energy demand by sector i in region r
β_{jir}	Share of liquid fossil fuel j in energy demand by sector i in region r (i $\notin$ FF, j $\in$ LQ)
θ_{isr}^{M}	Share of imports of good i from region s to region r
θ_{ir}^{A}	Share of domestic variety in Armington good i of region r
θ_{Cr}^{E}	Share of fossil fuel composite in aggregate household consumption in region r
γ_{ir}	Share of non-energy good i in non-energy household consumption demand in region r
θ_{iCr}^{E}	Share of fossil fuel in household energy consumption in region r

Table I.5 Endowments and emissions coefficients

$\bar{L}_r$	Aggregate labor endowment for region r
$\bar{K}_r$	Aggregate capital endowment for region r
$\bar{Q}_{ir}$	Endowment of natural resource i for region r (i $\in$ FF)
$\bar{B}_r$	Balance of payment deficit or surplus on region r (note: $\sum_r \bar{B}_r = 0$)
$\bar{CO}_{2r}$	Endowment of carbon emission rights in region r
$a_i^{CO_2}$	Carbon emissions coefficient for fossil fuel i ($i \notin FF$)

Table I.6 Elasticities

η	Transformation between production for the domestic market and production for the export	2
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.8
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}.	$\mu_{COA} = 0.5$ $\mu_{CRU} = 1.0$ $\mu_{GAS} = 1.0$
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.3
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_A	Substitution between the import aggregate and the domestic input	4
σ_M	Substitution between imports from different regions	8

Table I.6 Continued

σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

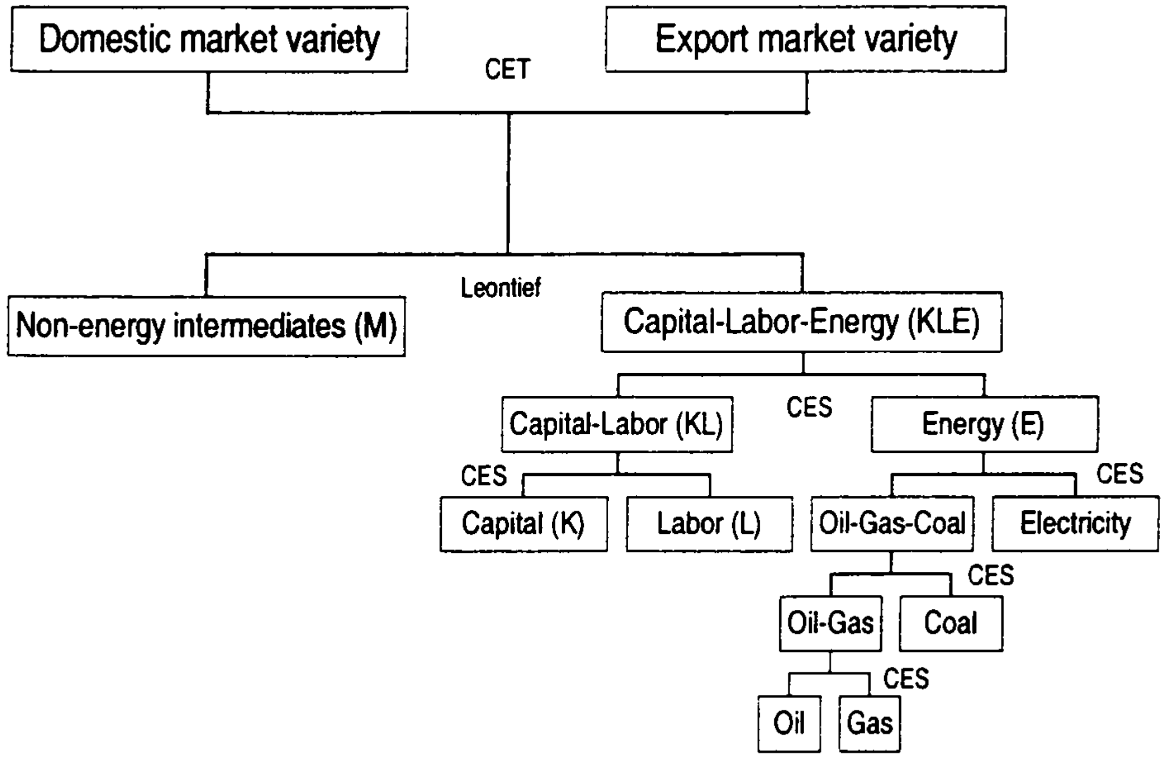

Figure I.1. Nesting in non-fossil fuel production.

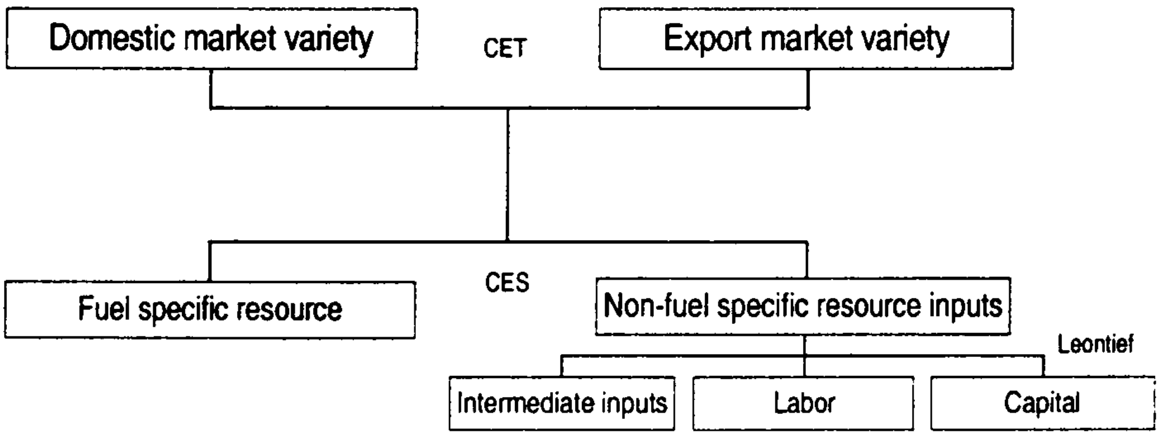

Figure I.2. Nesting in fossil fuel production.

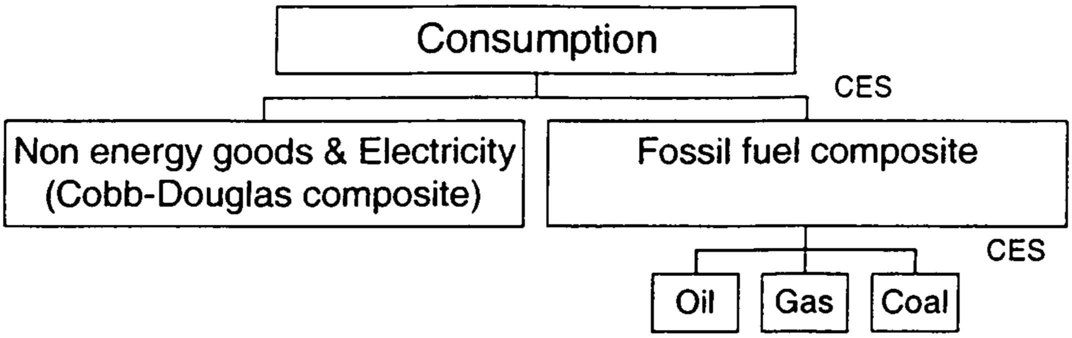

Figure I.3. Nesting in household consumption.

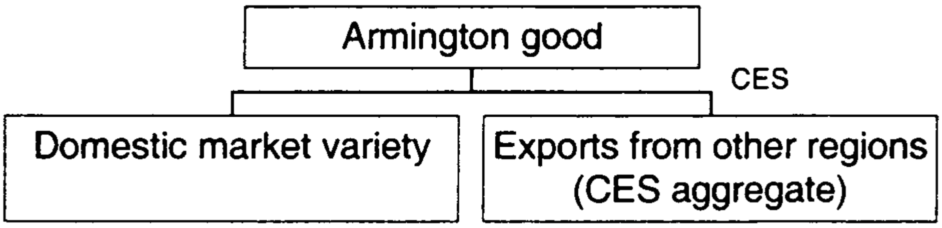

Figure I.4. Nesting in Armington production.

Appendix II: Sensitivity Analysis – Detailed Results

Table II.1 Welfare decomposition for changes in crude oil supply elasticities

	Domestic Market Effect (in % HEV)			Total Policy Effect (in % HEV)			International Spillover (in % of Total Policy Effect)		
	low	ref	high	low	ref	high	low	ref	high
CAN	−0.69	−0.69	−0.69	−0.91	−0.88	−0.85	24	21	18
CEA	0.00	0.00	0.00	0.41	0.29	0.20	100	100	100
EUR	−0.14	−0.14	−0.14	−0.04	−0.06	−0.08	−249	−116	−68
FSU	0.00	0.00	0.00	−1.21	−1.03	−0.90	100	100	100
JPN	−0.44	−0.44	−0.44	−0.27	−0.30	−0.32	−61	−47	−37
OOE	−0.13	−0.13	−0.13	−0.64	−0.65	−0.65	80	81	81
USA	−0.36	−0.36	−0.36	−0.37	−0.40	−0.41	3	9	13
ASI	0.00	0.00	0.00	0.21	0.14	0.08	100	100	100
BRA	0.00	0.00	0.00	0.12	0.09	0.06	100	100	100
CHN	0.00	0.00	0.00	0.24	0.20	0.17	100	100	100
IND	0.00	0.00	0.00	0.36	0.27	0.20	100	100	100
MPC	0.00	0.00	0.00	−1.39	−0.99	−0.70	100	100	100
ROW	0.00	0.00	0.00	−0.11	−0.08	−0.06	100	100	100

Table II.2 Welfare decomposition for changes in Armington elasticities

	Domestic Market Effect (in % HEV)			Total Policy Effect (in % HEV)			International Spillover (in % of Total Policy Effect)		
	low	ref	high	low	ref	high	low	ref	high
CAN	-0.78	-0.69	-0.60	-0.91	-0.88	-0.87	14	21	31
CEA	0.00	0.00	0.00	0.30	0.29	0.28	100	100	100
EUR	-0.14	-0.14	-0.13	-0.04	-0.06	-0.07	-211	-116	-78
FSU	0.00	0.00	0.00	-0.98	-1.03	-1.39	100	100	100
JPN	-0.47	-0.44	-0.43	-0.27	-0.30	-0.32	-70	-47	-36
OOE	-0.15	-0.13	-0.09	-0.72	-0.65	-0.62	79	81	85
USA	-0.38	-0.36	-0.32	-0.34	-0.40	-0.41	-12	9	23
ASI	0.00	0.00	0.00	0.10	0.14	0.16	100	100	100
BRA	0.00	0.00	0.00	0.0 2	0.09	0.08	100	100	100
CHN	0.00	0.00	0.00	0.14	0.20	0.22	100	100	100
IND	0.00	0.00	0.00	0.27	0.27	0.25	100	100	100
MPC	0.00	0.00	0.00	-1.32	-0.99	-0.83	100	100	100
ROW	0.00	0.00	0.00	-0.22	-0.08	-0.01	100	100	100

Table II.3 Welfare decomposition for changes in capital mobility

	Domestic Market Effect (in % HEV)		Total Policy Effect (in % HEV)		International Spillover (in % of Total Policy Effect)	
	ref	gkm	ref	gkm	ref	gkm
CAN	-0.69	-0.85	-0.88	-0.81	21	-5
CEA	0.00	0.00	0.29	0.15	100	100
EUR	-0.14	-0.15	-0.06	-0.07	-116	-119
FSU	0.00	0.00	-1.03	-0.97	100	100
JPN	-0.44	-0.51	-0.30	-0.31	-47	-65
OOE	- 0.13	-0.13	-0.65	-0.60	81	78
USA	-0.36	-0.36	-0.40	-0.37	9	3
ASI	0.00	0.00	0.14	0.06	100	100
BRA	0.00	0.00	0.09	0.02	100	100
CHN	0.00	0.00	0.20	0.17	100	100
IND	0.00	0.00	0.27	0.17	100	100
MPC	0.00	0.00	-0.99	-0.94	100	100
ROW	0.00	0.00	-0.08	-0.11	100	100

Table II.4 Welfare decomposition for changes in MCFs

	Domestic Market Effect (in % HEV)			Total Policy Effect (in % HEV)			International Spillover (in % of Total Policy Effect)		
	ref	MCF10	MCF25	ref	MCF10	MCF25	ref	MCF10	MCF25
CAN	–0.69	–0.35	0.19	–0.88	–0.45	0.23	21	22	19
CEA	0.00	0.00	0.00	0.29	0.30	0.31	100	100	100
EUR	–0.14	–0.07	0.05	–0.06	0.03	0.19	–116	289	75
FSU	0.00	0.00	0.00	–1.03	–1.03	–1.03	100	100	100
JPN	–0.44	–0.27	–0.01	–0.30	–0.12	0.16	–47	–129	109
OOE	–0.13	–0.01	0.16	–0.65	–0.51	–0.28	81	97	155
USA	–0.36	–0.14	0.21	–0.40	–0.14	0.24	9	6	13
ASI	0.00	0.00	0.00	0.14	0.14	0.15	100	100	100
BRA	0.00	0.00	0.00	0.09	0.09	0.09	100	100	100
CHN	0.00	0.00	0.00	0.20	0.20	0.21	100	100	100
IND	0.00	0.00	0.00	0.27	0.27	0.27	100	100	100
MPC	0.00	0.00	0.00	–0.99	–0.98	–0.96	100	100	100
ROW	0.00	0.00	0.00	–0.08	–0.07	–0.07	100	100	100

Table II.5 Welfare decomposition for changes in the US compliance with Kyoto

	Domestic Market Effect (in % HEV)		Total Policy Effect (in % HEV)		International Spillover (in % of Total Policy Effect)	
	ref	no_usa	ref	no_usa	ref	no_usa
CAN	–0.69	–0.69	–0.88	–0.73	21	5
CEA	0.00	0.00	0.29	0.11	100	100
EUR	–0.14	–0.14	–0.06	–0.10	–116	–36
FSU	0.00	0.00	–1.03	–0.44	100	100
JPN	–0.44	–0.441	–0.30	–0.36	–47	–23
OOE	– 0.13	–0.13	–0.65	–0.32	81	61
USA	–0.36	0.00	–0.40	0.01	9	100
ASI	0.00	0.00	0.14	0.00	100	100
BRA	0.00	0.00	0.09	0.04	100	100
CHN	0.00	0.00	0.20	0.05	100	100
IND	0.00	0.00	0.27	0.08	100	100
MPC	0.00	0.00	–0.99	–0.45	100	100
ROW	0.00	0.00	–0.08	–0.08	100	100

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