The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage

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Carbon dioxide emissions abatement in a group of countries can result in increased emissions in non-abating countries. This effect has been referred to as carbon leakage. The Kyoto Protocol calls for a number of industrialized countries to limit their emissions while other countries have no abatement commitments. This paper assesses the sectoral and regional determinants of the leakage in a static multi-sector, multi-regional computable general equilibrium model. In baseline estimates based on our model, the Kyoto Protocol leads to a carbon leakage rate of 10 percent. A decomposition technique is applied which attributes increases in CO_2 emissions by non-participating countries to specific sectors in the abating countries. This information is important for the debate on the tax exemptions for certain industries in the participating countries as it provides information for the most- and least-leakage contributing sectors of the economy. Additional calculations indicate the need for caution in the carbon tax design. Exemptions of any sector from a carbon tax are not justified because they lower welfare in a region. The degree of sectoral and regional data disaggregation, and international capital mobility do not change the leakage rate significantly. Fossil-fuel supply elasticities and trade substitution elasticities are crucial determinants for projecting the total world emissions of CO_2.

INTRODUCTION

Expanding economic activities can impose potentially irreversible environmental damage at local and global levels. A major example is "the greenhouse effect." This term refers to the effect of rising atmospheric concentrations of the greenhouse gases (where carbon dioxide, CO_2, is the major component) emitted from burning of fossil fuels and other human activity.

The Energy Journal, Vol. 22, No. 4.

The author is indebted to Thomas Rutherford and Jared Carbone for their discussions and comments. Three anonymous referees provided very useful suggestions and insights. Financial support from the United States Department of Energy is greatly acknowledged.

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According to different models (see, for example, Bruce et al. (1996) for a review), the greenhouse effect will cause significant global warming in the absence of policy intervention. The international response to climate change is a negotiating process embodied in the United Nations Framework Convention on Climate Change (UNFCCC (1992)) and its Kyoto Protocol (UNFCCC (1997)).

The Protocol calls for industrialized countries and economies in transition to limit their aggregate carbon equivalent emissions of the greenhouse gases (GHG) by the first part of the 21st century. The countries are listed in the protocol in the Annex B, so they are called Annex B countries. Developing countries have not committed themselves to reduce their greenhouse emissions because they have made minor contributions to global GHG concentrations. Unilateral emissions abatement by a subset of countries has raised serious doubts about its environmental efficiency. Abatement activities of the industrialized countries might result in a movement of the GHG emissions into the regions with no restrictions. This effect has been called *leakage*.

The main purpose of this paper is to estimate the region- and sector-specific contributions to the carbon leakage resulting from the Kyoto Protocol. As far as we know, this is the first study which assesses the leakage induced by a particular Annex B region. Information about the most- and least-leakage contributing sectors of the economy is important for the debate on a carbon tax design. An optimal carbon taxation attains a desirable global carbon reduction target at minimum cost. The first-best solution would apply a carbon tax in every country with a structure based on marginal abatement costs. The Kyoto Protocol, where some countries are exempt from abatement, leads to the second-best solution. The optimal tax rate must include additional costs as a result of the carbon leakage. The results of our study can be used as a starting point for the problem of optimal taxation in the second-best setting. We do not address this very challenging problem in the current paper. Another complicating issue of carbon tax design is sectoral exemptions from environmental regulations which for various reasons are applied in many countries. This paper addresses an important question of how sectoral exemptions affect the carbon leakage and regional welfare.

The carbon leakage rate is defined as the ratio of total increased CO_2 emissions by the non-Annex B countries to total emissions abatement by the Annex B country. This means that if the leakage rate is 40%, then a decrease in carbon dioxide emissions by Annex B countries by 100 million tons would lead to an increase in CO_2 emissions by non-Annex B countries by 40 million tons. As a result, the total decrease in the world CO_2 emissions would be 60 instead of 100 million tons. Estimates of the carbon leakage rate have obvious policy implications. If the leakage rate is high (close to 100%), then the decrease in carbon dioxide emissions by the Annex B countries assigned by the Kyoto Protocol has no effect on global emissions. An assessment of the leakage is a challenging task because of complex interactions between energy and non-energy markets. There are several potential sources for the carbon leakage (Felder and Rutherford (1993), Burniaux and Oliveira-Martins (2000), Kverndokk et al. (2000)).

The first one is due to the change in a demand on global fossil-fuel markets. Carbon abatement commitments may decrease the demand in the Annex B countries. This may lead to lower international prices for fossil fuels and increase in the fossil-fuel demand and emissions in the non-Annex B countries. The change in the non-Annex B energy demand depends on the fossil-fuel prices and substitution possibilities. Different fossil fuels have different carbon content.[1] The Kyoto Protocol might cause a fall in the price of oil relative to the price of coal. Based on a new price ratio, a non-Annex B country might substitute a relatively less carbon-intensive oil for carbon-intensive coal. Thus, the change in the fossil-fuel demand may even lead to a negative leakage. The magnitude of the leakage depends on the supply response by fossil-fuel producers. The decision about the rate of fossil-fuel extraction is an important determinant for the international price, and, therefore, for the carbon leakage.

The second major reason for the leakage comes from the higher costs of energy-intensive products in the Annex B countries. Carbon abatement might cause a shift of production to the non-Annex B countries due to the change in the competitiveness of the energy-intensive industries. It will lead to a positive carbon leakage. Also, the changes in terms of trade and regional income (for example, a change in oil revenue greatly affects an oil-exporting country's income) may cause positive or negative leakage.

As reported by the Energy Modeling Forum (EMF, (2000)), the current models have the following magnitudes for the leakage rate: 8% (G-Cubed), 9% (GTEM), 11% (Gemini-E3), 14% (WorldScan), 26% (MS-MRT), 34% (MERGE4). Also, OECD (Burniaux and Oliveira-Martins (2000)) has reported that their leakage estimate with the GREEN model is 5%. These estimates are reported for the scenario where CO_2 emission permits are non-tradable between countries. According to the existing models, permit trading decreases the carbon leakage rate approximately by half.

The goal of this paper is not to provide yet one more estimate of the leakage rate but to decompose the contributions to the leakage at regional and sectoral levels. The existing models evaluate an increase in the emissions in a particular non-abating region. The novelty of this paper is that it investigates the origin of the leakage, i.e., what sector in what abating region causes the increase in emissions in a particular non-abating region. An important implication of the study is whether leakage effects justify sectoral exemptions from carbon taxation. The basis for our research is a static large-scale computable general equilibrium (CGE) model of the world economy. To assess

1. The ratio of carbon in coal: oil: gas is 1 : 0.75 : 0.57.

the economic implications of the Kyoto Protocol, a decomposition procedure described by Harrison et al. (1999) is applied.

The Kyoto Protocol is a complex agreement with specific ground rules to be worked out at future negotiating sessions. A single model cannot include all features of the agreement. Therefore, there are certain limitations to the current study. This paper considers the regional and sectoral contributions to carbon leakage without introducing flexible mechanisms included in the Kyoto Protocol: permit trading, joint implementation, and the clean development mechanism. The economic effects of the flexible mechanisms crucially depend on how the rules of those projects are structured and, as of today, they are still undefined.[2] The Kyoto Protocol defines its targets in terms of six greenhouse gases. Due to the paucity of the data, we do not track the full range of gases. This paper focuses on carbon dioxide equivalent data. Recently, several authors (Burniaux (2000) and Manne and Richels (2000b)) used a multi-gas approach to the analysis of the costs of complying with the Kyoto Protocol, but implementing their approach in a multi-sectoral framework requires data which are not available.

Key findings of our paper can be summarized as follows. The leakage rate is 10.5% for the baseline values of the model. The economic sectors in which the carbon tax contributes the most to the leakage are the chemical industry (it contributes 2.1% to the total 10.5% leakage, or a 20% share), the iron and steel industry (16%), and final demand (15%). Some sectors, like final demand, transport, dwellings, or services, have high contributions because of their large size. Therefore, two ratios are introduced for assessing relative contributions. The leakage-emissions ratio (LE) relates emissions increase in the non-Annex B countries due to a carbon tax in a particular region or sector to total CO_2 emissions in that region or sector. Accordingly, the leakage-abatement ratio (LA) shows how leakage induced by a particular sector or region is related to abatement in that sector or region. Adjustment for total emissions and the magnitude of abatement shows that mining and the non-ferrous metal industry make relatively high contributions to the leakage along with the iron and steel, and chemical industries.

The leakage can be reduced if carbon abatement is imposed upon those sectors which will not move to another country to pollute. Indeed, our model shows that the exemptions in the chemical, the iron and steel, and the non-ferrous metal industries reduce the leakage. However, sectoral exemptions from carbon regulations are not justified on the basis of economic efficiency. Holding the Annex B emissions constant, exemptions for some sectors imply increased tax rates for others and a decrease in regional welfare.

2. For a discussion of different designs of the flexible mechanisms, see, for example, Weyant (1999) and Jepma and van der Gaast (1999).

The regions whose actions lead to the largest induced leakage are the European Union (36-51% of the contribution to carbon leakage based on different scenarios), the USA (28-34%), and Japan (13-18%). The regions have very different ratios of the induced leakage to their emissions abatement. In the baseline estimate, the USA share of the total emissions abatement equals 54% and the share of the induced leakage is 29%, while for the European Union these numbers are 26% and 41%, respectively. This result is influenced by a pattern of a global trade. It shows that, in relative terms, mitigation activities by the USA do not affect global CO_2 emissions as strongly as actions by Europe, Japan, Australia, and New Zealand. In fact, LE and LA ratios are the highest for Australia and New Zealand. The regions where the emissions will rise the most due to the implementation of the Kyoto Protocol are China (24-32% of the total increase) and the Middle East countries (24-30%). The relations between the following regions are the major contributors to the leakage: USA-Middle East, Europe-South Africa, Japan-China, and USA-China. A consideration of the sectoral incidence of carbon taxes in the Annex B regions leads to the following results. China will be affected the most by the tax on the iron and steel sector in Japan, then by the tax on the chemical industry in the USA, and by the tax on the chemical industry in the European Union.

It is usually proposed that a carbon tax should be levied on fossil fuels according to their carbon content. Our calculations show that, in absolute terms, the tax on oil has almost the same contribution (41.8%) to the leakage as the tax on coal (42.4%). The carbon tax on gas contributes 15.8%. As such, the ratio of the leakage contribution for taxes on coal:oil:gas is 1:0.99:0.37. However, the ratio adjusted for the total emissions from a particular fossil fuel (LE ratio) is 1:0.69:0.47, which is close to the relative carbon content of the fossil fuels.

We tested our results with respect to different values of fossil-fuel supply elasticity and Armington elasticity. Changing the fossil-fuel supply elasticity from 0.5 to 20 leads to a decrease in the leakage rate from 15 to 5%. A change in Armington elasticity of substitution between domestic and imported goods from 1 to 8, and a corresponding change in the substitution elasticity between imported goods from 4 to 16 results in an increase in the leakage rate from 7 to 15%. Our model shows that the degree of the international capital mobility is not a very influential determinant of the leakage rate. Eliminating restrictions on international capital movements increases the leakage rate approximately by 15%. These results are robust with respect to the degree of a sectoral disaggregation in the model. However, the differences are bigger in the case of the regional disaggregation. The leakage rate is not changed much with a disaggregation, and turns out to be about 10% for the values assumed in the model.

The remainder of the paper is organized in the following way. Section 2 describes the GTAP-EG model and data. The decomposition procedure which attributes increases in the CO_2 emissions in individual non-Annex B countries to a sector-specific tax in an abating region is outlined in section 3. Section 4 discusses the results of decomposing the carbon leakage at a region- and sector-specific level. A sensitivity analysis with respect to a range of alternative model specifications is provided, including the tests of the model with the different values of fossil-fuel supply elasticity and Armington elasticity. Section 5 concludes.

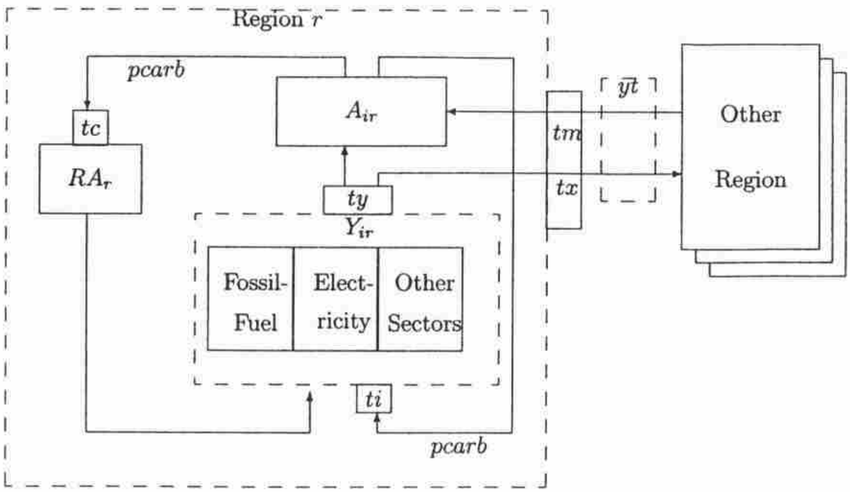
2. THE GTAP-EG MODEL

The model employed in this paper is based on the GTAP-EG dataset (Rutherford and Paltsev (2000)), which consists of 45 regions and 23 production sectors. Each region incorporates markets for non-energy goods, *C*, electricity, *E*, and non-electric energy, *N*. Non-electric energy includes: oil, gas and coal. Crude oil may be produced domestically or imported, and it is then refined prior to delivery as an input to production and final demand. Final energy products are supplied as inputs both to production and to final demand. Consumption in each region is associated with utility maximization by a representative agent subject to a budget constraint. The agent supplies primary factors (capital, *K*, labor, *L*, and energy resources, *R*) to non-energy and energy sectors. Factor income of each representative agent is then allocated to the purchase of energy (*E* and *N*), non-energy goods (*C*), and investment (*I*). Regions are connected with the global economy through trade in energy and non-energy goods. All commodities, except electricity, are traded internationally. The flows are implemented in the model in the following way. In the model there are three types of produced commodities, fossil-fuel, non-fossil fuel commodities, and electricity. The model assumes that goods produced in different regions are qualitatively distinct (Armington (1969)). This implies that trade in goods is represented as flows between pairs of countries rather than from individual countries and an integrated global market. Every bilateral trade flow requires its own transportation services. Primary factors in each region include labor, capital and fossil-fuel resources. Labor is mobile within domestic borders but cannot move between regions. Capital can be global or region-specific. Natural resources are sector-specific.

In the GTAP-EG model, an economy in region *r* consists of three production blocks. The block Y_{ir} is related to production, where fossil-fuel production has a different structure from other production sectors. A production block for Armington supply, A_{ir}, represents an aggregation between domestic and import varieties and across imports from different trading partners. This aggregate good is used then for private consumption and as an intermediate input to production. A production block *yt* describes the provision of international transport services. In each region the representative agent (described by RA_r) depicts a collective decision process for allocating income to households and to a government.

Regions may apply domestic carbon taxes. Carbon tax revenue is collected by the representative agent in each region. Within this model, the carbon tax policy is equivalent to an emission permit system where the permit price coincides with the carbon tax, which is returned to consumers in a lump-sum fashion. There are also taxes on output, *ty*, intermediate inputs, *ti*, consumption, *tc*, export, *tx*, and import, *tm*. Figure 1 depicts the structure of the model.

Figure 1. Structure of the GTAP-EG Model



Fossil fuel production activities include extraction of crude, gas, and coal. Production has the structure shown in Figure A.1 in Appendix 1, where a value to the right of the arc represents an elasticity. Fossil fuel output (*y(xe)*, where *xe* is one type of exhaustible energy: crude, gas, coal) is produced as an aggregate of a resource input (*pr(xe)*) and a non-resource input composite. The non-resource input for the production is a fixed - coefficient (Leontief) composite of labor (*pl*) and the Armington aggregation (*pa(i)*) of domestic and imported intermediate input from a production sector *i*. The elasticity of substitution between *pa* and *pl* equals zero (*id:0*), which characterizes a Leontief composite. The elasticity of substitution ($s{:}esub_{es}$) between the resource input and the non-resource input composite depends on the value share of resource inputs in fossil fuel supply. Non-fossil fuel production (including electricity and refining) has a different structure. Figure A.2 illustrates the nesting and typical elasticities employed in production sectors other than fossil fuels. Output is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an energy-primary factor composite. The energy-primary factor composite is a constant-elasticity of substitution (CES) function with elasticity = 0.5. Primary factor inputs of labor and capital are aggregated through a Cobb-Douglas production function (*va:1*). The energy composite is a CES function of electricity versus other energy inputs, coal versus liquid fuels, and oil versus gas.

Armington aggregation activity generates intermediate demand for production and final demand for consumption as a mix of domestic and imported goods as imperfect substitutes. It is assumed that the domestic-imports elasticity of substitution (*d*) equals four, while the elasticity of substitution among import sources (*m*) equals eight. Imports from every region require transportation services (*pt*) which are implemented as shown in Figure A.3 for region *S*. The international transport services are assumed to be a Cobb-Douglas composite of goods provided in the domestic markets in each region. Final demand has the structure shown in Figure A.4. Utility in each country is a constant elasticity aggregate of non-energy consumption and energy. The non-energy composite is in turn a Cobb-Douglas aggregate of different goods while final energy is a Cobb-Douglas aggregate of electricity, oil, gas, and coal. As has already been noted, the full GTAP-EG dataset has 45 regions and 23 sectors. In this paper, calculations for different aggregations of the full dataset have been made. For the sake of compactness, most of the results in this paper are reported for the dataset (called a *base* dataset), which is obtained from the full GTAP-EG by aggregating into 13 regions and 23 sectors. Regions and sectors for the base dataset are listed in Appendix 2.

3. A DECOMPOSITION METHOD

General equilibrium analysis is extremely valuable because it can account for interrelated and balanced transactions between all regions and sectors in the world economy. The resulting change in the endogenous variable of interest (such as welfare, CO_2 emissions, etc.) depends on many direct and indirect mechanisms. As various partial effects, which may work in opposite directions, contribute to the overall effect, it is sometimes very difficult to explain in depth the aggregate policy outcome. Therefore, procedures which allow the decomposition of simulation results with respect to exogenous shocks are very helpful for understanding the importance of a particular policy instrument on overall change in an endogenous variable.

In this paper, a method described by Harrison et al. (1999) is used for the decomposition of a change in CO_2 emissions in the non-Annex B regions due to the restrictions in specific sectors of the Annex B. We denote CO_2 emissions in a non-Annex B region s as Z^s. The emissions might change because of the change in exogenous policy instruments, such as a carbon tax X in a sector i of the Annex B region b. Based on certain values of the instrument variable, X_{ib}, the GTAP-EG model gives a numerical value for Z^s, so it can be expressed as a function

$$Z^s = F(X_{ib}) \tag{1}$$

A change in the carbon taxes X_{ib} leads to an aggregate change in the outcome for the non-Annex B region's CO_2 emissions from Z^s to Z^{s*}. The objective of the analysis is to create a consistent decomposition of the aggregate change $\Delta Z^s = Z^s - Z^{s*}$ into the changes due to a particular sector-specific carbon tax in a particular Annex B region, such that

$$\Delta Z^s = \sum_{ib} \Delta Z^s_{ib} \tag{2}$$

where ΔZ_{ib}^s is the change in the CO_2 emissions in a region s due to the change in the carbon tax X_{ib} in a sector i of a region b. When F is non-linear, the total change in Z^s is path-dependent, i.e., the decomposition is sensitive to the ordering of changes in the policy instruments X_{ib}. It is assumed that the policy instruments are introduced simultaneously. Therefore, the change in the carbon tax X_{ib} can be represented as

$$\Delta X_{ib} = X^1_{ib} - X^0_{ib} \tag{3}$$

where X_{ib}^1 is the final value and X_{ib}^0 is the starting value of the policy instrument. The path between these two points can be constructed as follows.

$$X_{ib} = X^0_{ib} + t\Delta X_{ib} \tag{4}$$

where t is a scalar which parameterizes the change in X_{ib}. When $t=0$, X_{ib} is at its starting value. When $t=1$, the carbon tax is at its final value.

For a given value of t we can write

$$\frac{\partial Z^s}{\partial t} = \sum_{ib} \frac{\partial F}{\partial X_{ib}} \frac{\partial X_{ib}}{\partial t} = \sum_{ib} \frac{\partial F}{\partial X_{ib}} \Delta X_{ib} \tag{5}$$

Then the total change in Z^s is given by the following expression.

$$\Delta Z^s = \int_{t=0}^{t=1} \frac{\partial Z^s}{\partial t} dt = \int_{t=0}^{t=1} \left(\sum_{ib} \frac{\partial F}{\partial X_{ib}} \Delta X_{ib} \right) dt = \sum_{ib} \left[\Delta X_{ib} \int_{t=0}^{t=1} \frac{\partial F}{\partial X_{ib}} dt \right] = \sum_{ib} \Delta Z^s_{ib} \tag{6}$$

Equation (6) gives us the method of calculating the decomposition which is applied in this paper. That is, we start by calculating the partial derivatives $\partial F/\partial X_{ib}$ for a particular t, then integrate these derivatives over the whole range of t. The resulting integral is multiplied by the change in the policy instrument ΔX_{ib} and summed over all policy instruments. The method is applied in the following way. First, the Business-As-Usual (BAU) scenario is considered. There are no limits on CO_2 emission in this case. It is important to choose an appropriate BAU scenario because all counterfactual experiments are compared against the BAU, and the magnitude of the results depends on the BAU projections for GDP, energy efficiency improvements, etc. In this paper, the estimates for the BAU case are taken from the Bohringer and Rutherford (2000) paper, where forward calibration to the year 2010 of the GTAP-EG dataset is done based on the U.S. Department of Energy (DOE (1998)) data.

Due to the path-dependency of the decomposition method, the sequence in which the policy instruments are implemented affects the results. In other words, if, let's say, the USA and Japan would introduce carbon taxes in 2008 and the rest of the Annex B parties would introduce them in 2010, then the magnitude of carbon leakage would be different in comparison to the case when all Annex B countries introduce carbon restrictions simultaneously. In this study, we assume that the Kyoto Protocol is going to be implemented by all parties at the same time.

To calculate the leakage rate, the CO_2 emissions are restricted to the quantities assigned by the Kyoto Protocol. The Protocol commits Annex B countries to the reduction of their aggregate CO_2 equivalent emissions on average by 5.2% below 1990 levels in the period from 2008 to 2012. The individual commitments by the Annex B regions as they are defined in the paper are shown in Table 1, where the Kyoto targets and each region's share in the total Annex B emissions are reported. Table 1 also presents the amount of 1990, 1995, and 2010 emissions, the regional shares and associated changes necessary to meet the Kyoto obligations. The USA, the European Union, and the former Soviet Union are the largest contributors to CO_2 emissions among the Annex B regions. Based on the forecasts, the share of the United States increases from 35 to 39% in 20 years, while the share of the former Soviet Union decreases from 21 to 17%. Considering the cutback necessary to meet the Kyoto target, the USA, Canada, and Japan have to decrease their emissions by one-third. The former socialist block (FSU and CEA) is not affected by the Kyoto Protocol due to structural changes and a decrease in economic growth. They are approximately at the target by the year 2010.

Table 1. CO_2 Emissions (million metric tons), Region's Share (%) in the Total Annex B Emissions, and the Reduction (%) by the Kyoto Protocol

	USA	CAN	EUR	JPN	OOE	FSU	CEA
Kyoto target	4532.3	401.9	3011.0	998.1	309.4	2904.6	934.0
Kyoto share	34.6	3.1	23.0	7.6	2.4	22.2	7.1
1990 emission	4873.4	427.5	3291.4	1061.8	288.3	2909.6	1003.8
1990 share	35.2	3.1	23.7	7.7	2.1	21.0	7.2
1990 change	-7.0	-6.0	-8.5	-6.0	7.3	-0.2	-7.0
1995 emission	5460.5	506.3	3599.4	1256.8	318.0	2548.9	763.0
1995 share	37.8	3.5	24.9	8.7	2.2	17.6	5.3
1995 change	-17.0	-20.6	-16.3	-20.6	-2.7	14.0	22.4
2010 emission	6600.0	590.3	3901.3	1452.0	381.3	2915.0	936.0
2010 share	39.3	3.5	23.3	8.7	2.3	17.4	5.5
2010 change	-31.3	-31.9	-22.8	-31.3	-18.9	-0.4	-0.2

In order to account for the change in CO_2 emissions, a quantity instrument such as emission permit is introduced to the GTAP-EG model. The quantity of permits in each region is limited to the Kyoto target. These permits can be used for production and final demand. In the BAU case the permit price is equal to zero because there are no restrictions on emissions. In a counterfactual experiment, the permit price is positive. The carbon permits are non-tradable between regions. As such, each region has a different permit price. The price is higher for the regions with a higher required emission abatement. To be able to decompose carbon leakage at a sectoral level, sector-specific carbon taxes are introduced. The results of the modeling are presented in the next section.

4. THE RESULTS

As it has already been noted, the mitigation efforts by the Annex B countries may affect the amount of CO_2 emissions in the rest of the world. The resulting carbon leakage is measured as the ratio of the additional emissions in the non-Annex B countries to the change in the CO_2 emissions in the Annex B countries. The decomposition technique allows us to estimate contributions to the global leakage rate for each sector and every Annex B country.

4.1 Regional Decomposition

The results of the decomposition at the regional level are presented in Table 2. The estimated leakage rate is 10.5%, which is to say if we denote the total decrease in CO_2 emissions by the Annex B countries (approximately 3600 Mt CO_2) as 100%, then the increase in CO_2 emissions by the non-Annex B countries in comparison to BAU scenario is about 380 Mt, or 10.5% of that number. The existing models estimate the magnitude of the total carbon leakage and an associated increase in the CO_2 emissions by the non-Annex B countries. Our calculations for the baseline case show that most of the increase in the emissions is going to happen in China (CHN, 3.16% in the total 10.5% leakage), the rest of the world region (ROW, 2.58%), the Middle East (MPC, 2.54%), and the rest of Asia (ASI, 1.37%). The results for disaggregated regions are available from the author upon request. The novelty of our model is that it allows us to obtain the magnitudes for the induced leakage. The corresponding numbers in Table 2 show which country's actions cause the increase in the non-Annex B emissions. The European Union and the USA are the largest contributors with 4.34% and 3.08% induced leakage, respectively. Compliance with the Kyoto Protocol by the Central European region (CEA) has no effect on the leakage rate. The model also calculates the contribution to the leakage from every pair of abating-nonabating regions. The region ROW has the highest increase (1.53% toward the total 10.5% leakage, or a 15% share of the total leakage) due to the change in CO_2 emission limits in the region EUR. The next two largest contributing pairs are CHN-EUR (1.12%) and MPC-USA (0.96%).

Table 2. Regional Decomposition

	USA	CAN	EUR	JPN	OOE	FSU	CEA	Total leakage
CHN	0.75	0.38	1.12	0.68	0.22	0.03	0.00	3.16
IND	0.20	0.03	0.19	0.10	0.03	0.01	0.00	0.56
BRA	0.11	0.02	0.09	0.05	0.01	0.00	0.00	0.28
ASI	0.45	0.06	0.53	0.25	0.07	0.01	0.00	1.37
MPC	0.96	0.15	0.88	0.40	0.11	0.04	0.00	2.54
ROW	0.61	0.11	1.53	0.26	0.08	0.01	0.00	2.58
Induced leakage	3.08	0.75	4.34	1.74	0.51	0.10	0.00	10.5

The resulting change in carbon leakage depends on many direct and indirect mechanisms, such as the degree of the required emission cutback, change in prices in different regions, and change in terms of trade. We found that the most important factor that affects the patterns of induced leakage is the corresponding patterns of bilateral trade. The numbers for a region's emissions and abatement as a share of the total Annex B emissions and abatement are helpful to depict the following results caused by the structure of global trade. For example, the USA has the largest CO_2 emissions and the largest abatement by the Kyoto Protocol, but their contribution to leakage is lower than that of the European Union. In order to assess relative contributions, two ratios are introduced. The leakage-emissions ratio (LE) relates emissions increase in the non-Annex B regions due to a carbon tax in a particular region or sector to total CO_2 emissions in that region or sector. Accordingly, the leakage-abatement ratio (LA) shows how leakage induced by a particular sector or region is related to abatement in that sector or region.

Table 3 shows the share of leakage, emissions, and abatement of a particular region as a percentage of the total Annex B numbers. The carbon restrictions introduced by the European Union and the USA lead to 41% and 29% of the total leakage, respectively. Table 3 also reports the ratios introduced above. The region OOE (Australia and New Zealand) has the highest LE ratio, i.e., in the case of introduction of the Kyoto Protocol, OOE induces the increase of 4.3 ton of CO_2 emissions in the non-Annex B per each 100 tons of its own emitted CO_2. This region also has the highest LA ratio, which tells us that for each 100 tons of CO_2 decrease, OOE induces 22.7 tons of CO_2 emissions in the non-Annex B countries. The adjusted leakage ratios show that despite having the largest CO_2 emissions, the USA is a modest contributor to the global leakage in relative terms.

Table 3. Regional Shares and Adjusted Leakage Ratios

	USA	CAN	EUR	JPN	OOE	FSU	CEA
% leakage	29.4	7.1	41.4	16.6	4.9	0.9	0.0
% emissions	39.3	3.5	23.3	8.7	2.3	17.4	5.5
% abatement	54.2	5.1	26.0	12.4	1.9	0.3	0.0
LE ratio	1.7	4.1	3.7	4.2	4.3	0.1	-0.5
LA ratio	5.5	12.9	16.3	13.3	22.7	2.8	-

The precision of the decomposition method depends on the numerical methods of calculating the line integral and derivatives. The values of the differences between the results obtained from the decomposition method and from the direct calculations are reported in Appendix 3.

4.2 Sectoral Decomposition

The same decomposition procedure allows us to estimate the sectoral contribution to the leakage. The results are represented in Table 4. It reports the data on which sector in which Annex B country causes an increase in the non-Annex B CO_2 emissions. The Central European region (CEA) and the food products industry (FPR) do not contribute to the leakage; therefore, they are not represented in the table. In absolute terms, the carbon tax on the chemical industry (CRP) is the major source for the emission migration. It contributes 2.08% in the total 10.5% leakage (or a 20% share). The carbon taxes on iron and steel industry (I_S), and final demand (FNL) are the next largest contributors. They induce the leakage at the rates of 1.70% and 1.56%, respectively.

It is also possible to rank the contributions to the leakage from carbon taxes by considering the sector and region where they are levied. The carbon tax on final demand in the USA is the leader here with 0.85% in 10.5% leakage. The taxes on the chemical industry in the European Union (0.80%) and the USA (0.75%) follow the lead. Different industries play different roles in the different regions. For example, in the USA contributions are the largest from the taxes on final demand, the chemical industry, and trade and transport, while for Japan the major contributors are the iron and steel industry, chemical industry, and dwellings. This particular result can be useful for an exploration of the question of tax exemptions for certain industries in different regions.

Table 4. Sectoral Decomposition

Sector	USA	CAN	EUR	JPN	OOE	FSU	Total contribution
CRP	0.75	0.14	0.08	0.31	0.04	0.03	2.08
I_S	0.27	0.08	0.64	0.54	0.07	0.08	1.70
FNL	0.85	0.07	0.47	0.17	0.01	-0.01	1.56
DWE	0.10	0.05	0.64	0.19	0.06	-0.02	1.01
SER	0.14	0.06	0.42	0.11	0.05	0.00	0.77
T_T	0.37	0.05	0.16	0.06	0.02	0.00	0.65
NFM	0.12	0.06	0.14	0.05	0.13	0.03	0.54
NMM	0.10	0.02	0.25	0.11	0.02	0.00	0.50
OMN	0.19	0.08	0.12	0.03	0.03	0.01	0.46
ELE	0.04	0.06	0.24	0.05	0.05	-0.01	0.43
PPP	0.05	0.04	0.11	0.03	0.01	0.00	0.23
OME	0.04	0.01	0.09	0.02	0.01	0.00	0.17
OMF	0.06	0.00	0.07	0.02	0.00	0.00	0.15
TRN	0.02	0.01	0.06	0.02	0.00	0.00	0.10
LUM	0.02	0.01	0.03	0.03	0.01	0.00	0.10
CNS	0.01	0.00	0.03	0.02	0.00	0.00	0.06
TWL	0.01	0.00	0.03	0.00	0.00	0.00	0.04
AGR	-0.05	0.00	0.04	0.01	0.00	-0.01	-0.0

Note: See Appendix 2 for list of all sectoral and regional identifiers in the dataset.

Table 5 reports the sectoral shares in leakage, total emissions and total abatement. Final demand, dwellings, transport and trade, services, and chemical industry have large shares in the total CO_2 emissions. Final demand, dwellings, and services are among the major contributors because of the size of these sectors and their extensive usage of electricity. As mentioned earlier, in addition to estimating leakage in absolute terms, it is informative to compare relative values. In the carbon tax design, sectors with high relative contribution should be taxed more heavily. Therefore, besides the above mentioned shares, Table 5 also reports the LE and LA ratios.

The importance of relative leakage can be illustrated by the examples of dwellings and services on one side, and the non-ferrous metal industry (NFM) and mining (OMN) on the other side. In absolute terms, services and dwellings are the major contributors to leakage, while the NFM and OMN sectors contribute rather moderately. However, if we adjust the leakage for sectoral CO_2 emissions, the picture is reversed. NFM and OMN have high ratios of induced leakage to their emissions, and dwellings and services have moderate relative leakage. It should be noted that some industries are among the leaders both in absolute and relative terms, such as the iron and steel industry and the chemical industry.

Table 5. Sectoral Shares and Adjusted Leakage Ratios

Sector	% of total leakage	% of total emissions	% of total abatement	LE ratio	LA ratio
CRP	19.9	10.5	20.9	4.3	20.5
I_S	16.2	6.2	20.7	5.8	28.2
FNL	14.9	19.1	16.6	1.7	10.5
DWE	9.7	12.4	24.9	1.7	6.9
SER	7.4	11.4	28.2	1.4	5.0
T_T	6.2	12.0	12.7	1.1	9.0
NFM	5.1	2.4	17.8	4.7	26.3
NMM	4.7	2.5	24.9	4.0	16.2
OMN	4.4	1.4	25.2	7.0	28.0
ELE	4.1	7.1	34.3	1.2	3.6
PPP	2.2	2.4	29.2	1.9	6.4
OME	1.6	2.3	25.7	1.3	5.2
OMF	1.5	1.4	28.7	2.0	7.0
TRN	1.0	1.3	27.9	1.3	4.7
LUM	0.9	1.1	26.8	1.5	5.7
CNS	0.5	1.3	17.7	0.5	2.9
TWL	0.0	1.3	26.8	0.3	1.2
AGR	0.0	3.7	14.6	-0.2	-1.2

A sector's high contribution to leakage could justify an exemption from the carbon tax to increase efficiency of global CO_2 reduction. However, exemptions in some sectors imply increased tax rates for others and higher costs for an economy as a whole. Based on the analysis of German environmental regulations, Bohringer and Rutherford (1997) concluded that exemptions can significantly increase the welfare cost of taxes. The cost of exemptions increases with the target level of emission reductions and with the share of the exempted sectors in economic activity and total emissions. Our calculations confirm their findings and show that exemption of any sector from the carbon tax decreases welfare. Table 6 illustrates the trade-off between the sectoral exemptions and the magnitudes of the change in welfare. Tax exemptions in the chemical, iron and steel, and non-ferrous metals sectors decrease the total carbon leakage but have a negative effect on regional welfare. Exemptions for dwellings, services, transport and trade sectors increase the leakage but also have a negative effect on welfare. As one can see, a tax exemption for a certain industry may increase or decrease total leakage. The sign depends on the mechanism through which this sector affects CO_2 emissions: energy markets or non-energy markets. The chemical and iron and steel industries are likely to move to non-abating regions due to the change in cost of production. Transport, services and dwellings are likely to affect the leakage through the change in demand for and, hence, change in international price for fossil fuels.

Table 6. Change in Welfare Due to the Sectoral Exemptions

	CRP	I_S	DWE	SER	T_T	NFM	NMM	OMN
% contribution to leakage	19.9	16.2	9.7	7.4	6.2	5.1	4.7	4.4
% Δ in leakage if exempted	-5.8	-3.1	5.0	4.4	3.5	-0.6	0.0	-0.9
% Δ in welfare in								
USA	-0.2	-0.0	-0.1	-0.1	-0.1	-0.0	-0.0	-0.0
CAN	-0.6	-0.1	-0.3	-0.4	-0.6	-0.1	-0.1	-0.2
EUR	-0.1	-0.1	-0.2	-0.1	0.1	-0.0	-0.0	0.0
JPN	-0.1	-0.4	-0.1	-0.1	0.1	-0.0	-0.1	0.0
OOE	0.0	0.0	-0.0	-0.0	0.1	-0.0	0.0	-0.0
FSU	-0.0	-0.2	0.0	0.0	0.1	-0.1	-0.0	-0.0
CEA	0.1	-0.0	0.1	0.0	-0.0	-0.0	0.0	0.0

It should be noted that the GTAP-EG model (as most of the Kyoto-related models) does not account for the possible scenario where the OPEC countries decrease their oil extraction and change the world price in anticipation of the effects of the Kyoto Protocol. A dynamic model of the OPEC market power by Berg et al. (1997) shows that OPEC will reduce its production in order to maintain a high price level when the carbon tax is introduced.

4.3 Fossil-fuel Contributions

Our model also distinguishes regional and sectoral leakage contributions by the type of fossil fuel tax. Tables 7 and 8 present the results for specific fossil fuels. A tax on oil in the USA is the major contributor (a 23.4% share) to induced leakage, followed by a tax on coal in Europe (19.5%), and a tax on gas in Europe (13.7%). In terms of increased non-Annex B emissions, the tax on coal will have the greatest effect in China (a 21% share) and the tax on oil will have the greatest effect on the Middle East region (14.3%).

At a sectoral level, the impact of the taxes on different fossil fuels also varies. As one can see from Table 8, the chemical industry, final demand, and transport are sensitive to the tax on oil, while the iron and steel industry and dwellings are most affected by the tax on coal. It is possible to use the decomposition procedure to estimate the impact of a certain fossil-fuel tax in a particular sector of a particular Annex B country. In the interest of briefness, these results are not reported here. They are available from the author upon request.

Table 7. Regional Leakage Contribution of Different Fossil Fuel Taxes (%)

Annex B	coal	oil	gas	non-Annex B	coal	oil	gas
USA	9.6	23.4	-2.8	CHN	21.3	8.6	-0.6
CAN	3.7	2.8	0.1	IND	2.2	3.8	-0.6
EUR	19.5	9.9	13.7	BRA	0.9	2.3	-0.4
JPN	6.7	6.9	3.2	ASI	3.4	8.5	1.5
OOE	3.6	0.0	0.8	MPC	2.6	14.3	8.4
FSU	-0.2	-0.9	1.2	ROW	12.1	4.2	7.5
Total	42.4	41.8	15.8	Total	42.4	41.8	15.8

Besides the magnitude of the total contributions to the leakage in absolute terms, it is important to estimate the leakage induced by a tax on a certain fossil-fuel in relationship to the total CO_2 emissions from that fossil fuel. In absolute terms, the tax on oil has almost the same contribution (41.8%) to leakage as the tax on coal (42.4%), and the carbon tax on gas contributes 15.8%. Hence, the ratio of the leakage contribution for taxes on coal:oil:gas is 1:0.99:0.37. The ratio adjusted for the total emissions from a particular fossil fuel (LE ratio) is 1:0.69:0.47. This ratio is close to the carbon content of fossil fuels.

Table 8. Sectoral Leakage Contribution of Different Fossil Fuel Taxes (%)

Sector	coal	oil	gas	Sector	coal	oil	gas
CRP	3.6	14.2	3.0	NFM	3.1	1.0	1.1
I_S	12.6	2.4	2.0	NMM	2.6	1.1	1.1
FNL	0.4	11.3	3.8	OMN	1.8	1.7	0.9
DWE	5.1	1.9	2.9	ELE	3.7	0.3	0.1
SER	4.8	1.5	1.2	PPP	1.4	0.5	0.2
T_T	0.4	5.9	0.1	Total	42.4	41.8	15.8

4.4 Elasticities

The results of CGE modeling crucially depend on several parameters, including elasticities. In many cases, there is no consensus about the exact values. The usual approach then is to perform a sensitivity analysis to show the effects of different values of elasticities. For most of the elasticities employed in this study we have used the values adopted in the GTAP model (Hertel (1997)). In the baseline case we have assumed a unit elastic fossil-fuel supply.

The Armington elasticity between domestic and imported goods is four, and the elasticity between imports from various countries is eight. We tested our results and found that the major factors affecting leakage are elasticity of fossil fuel supply and Armington elasticities.

The fact that the elasticity of supply plays a crucial role has been stressed by several authors (see, for example, Manne and Richels (2000a), Light et al. (1999), and Burniaux and Oliveira-Martins (2000)). However, there is no agreement on the exact values of the supply elasticities for fossil fuels, especially for coal. For example, based on their econometric analysis, Light et al. (1999) argue that coal supply elasticity is low, and based on that assumption they found leakage of about 20%. Their work is in contrast to the results from Burniaux and Oliveira-Martins (2000), whose claim about the high coal elasticity in the GREEN model leads to the much lower magnitude for the leakage of 5%.

The results of the model are tested with respect to different values of fossil-fuel supply elasticity. Table 9 shows the results for different values of supply elasticity. The first three rows represent the cases where we change the elasticity for a particular fossil-fuel and keep other values at unity. The last row reports the numbers for the cases where we change the supply elasticities for all fossil fuels. Based on these different values, the leakage rate ranges from 5 to 15%. The higher the elasticity, the lower the magnitude of leakage. The coal supply elasticity is indeed the major determinant for leakage. However, oil and gas supply matters as well.

Table 9. Leakage Rate for Different Fossil-fuel Supply Elasticity

	0.5	5	10	20
coal	12.3	8.3	7.9	7.7
oil	11.9	9.1	8.9	8.7
gas	11.7	9.3	9.1	9.0
all	14.7	5.8	5.1	4.7

While fossil-fuel supply elasticities represent the leakage mechanisms that operate through energy markets, the trade substitution elasticity is an important factor for non-energy markets. An increase in production costs of energy-intensive industries in the Annex B regions leads to the loss of their market share in a global market. Higher values of Armington elasticity mean an easier switch to a product from another region. As a result, the abating industry would lose a greater proportion of its market share. Burniaux and Oliveira-Martins (2000) found that the leakage rate is not very sensitive to the Armington elasticities. Their result contrasted with the finding by Bernard and Vielle (2000) who reported that the leakage rate increases substantially with trade substitutability. As has already been mentioned in Section 2, the Armington trade elasticity has two nests. One nest describes how easily one can substitute domestic goods and services with imports (we denote this nest as *d*). Another nest shows the substitutability among imports from various countries (*m*). Table 12 represents the results of the leakage rate estimation for the values of $d = 1$, 4, 8, and the values of $m = 4$, 8, 16. Our simulations confirm the result that Armington elasticity is an important factor in determining the leakage rate. Higher Armington elasticities lead to the higher leakage.

Table 10. Leakage Rate for Different Armington Elasticity

	4	8	16
1	6.9	8.2	10.3
4	9.4	10.5	13.0
8	11.8	13.0	15.4

4.5 Aggregation

Most of the existing models employed in the Kyoto-related research are based on very aggregated datasets. Usually, the models consider about 8-20 regions of the world and up to 10 sectors, five or six of which are energy sectors, such as coal, gas, oil, crude, heat, and electricity, leaving the analysis with only a few industrial sectors. Building global detailed datasets is a very challenging task. It is hard to obtain disaggregated data of a good quality. Sometimes even when data are available, calculations for the datasets with high dimensionality might be very complicated or time consuming. Therefore, it is important to explore how the level of aggregation affects the results. For this purpose, we run the GTAP-EG model for a variety of aggregations to assess the bias.

Table 11 summarizes the results of the decomposition procedure described above for the different levels of aggregation. The table shows the Annex B region's contribution to the induced leakage and the non-Annex B region's contribution to the increase in pollution. It also presents the data on the shares of the sectoral carbon taxes and the magnitude of the leakage rate. Cases A, B, and C have the same number of regions but different sectoral aggregation. The sectors in case C are aggregated into two non-energy sectors (Y and EIS) in the same fashion as in Bohringer and Rutherford (2000) and Rutherford and Paltsev (2000).[3] In case B, some of the Y and EIS sectors are disaggregated. The results are reported in the following way. For datasets with more than 13 regions and 8 sectors, the individual sectoral and regional contributions are integrated into the corresponding aggregated sectors and regions. Therefore, it

3. The energy-intensive sector (EIS) consists of the following industries: I_S, CRP, NFM, NMM, TRN, and PPP. The Y sector combines T_T, AGR, OME, OMN, FPR, LUM, CNS, TWL, OMF, SER, and DWE.

is possible to compare the results for disaggregated datasets with the models where sectors Y and EIS are treated as homogeneous. A comparison between cases A, B, and C shows that sectoral aggregation does not result in substantial differences in the contribution to leakage.

Table 11. Decomposition and Leakage for Different Scenarios

Dataset	A (base) 13x23	B 13x15	C 13x8	D 45x8	E 13x8gl
Regions					
Annex B					
USA	29	29	28	34	28
CAN	7	7	8	7	8
EUR	41	41	43	36	40
JPN	17	17	15	18	18
OOE	5	5	5	4	5
FSU	1	1	1	1	1
CEA	0	0	0	0	0
Non-Annex B					
CHN	30	30	31	24	32
IND	5	5	5	5	4
BRA	3	3	2	3	2
ASI	13	13	13	13	13
MPC	24	24	24	30	25
ROW	25	25	25	25	24
Sectors					
Y	32	35	34	30	37
EIS	49	47	46	50	46
ELE	4	4	5	1	4
FNL	15	14	15	19	13
Leakage Rate	10.5	10.4	9.6	7.4	10.8

Case D depicts the fully disaggregated regions as they are defined in the GTAP-EG dataset. It is found that regional disaggregation lowers leakage while sectoral disaggregation works in the opposite direction. While running the disaggregated model does not greatly change the sectoral contributions, the regional disaggregation has a substantial effect on the magnitude of the results. Regional disaggregation lowers the leakage induced by the European Union (from 43% to 36%) and increases the induced leakage for the USA (from 28% to 34%). It also affects the magnitude of the results for China and the Middle East. However, the qualitative conclusions from the modeling are still the same.

4.6 International Capital Mobility

There is another potential mechanism for leakage which is related to capital movements and operates through non-energy markets. Besides losing the market shares due to carbon restrictions, energy-intensive industries in the Annex B regions might find that foreign direct investment is reallocating into the non-abating regions. A change in a pattern of foreign direct investment affects the magnitude of the leakage because new carbon-intensive production facilities will be moved in the non-Annex B countries. A degree of capital mobility is a key parameter to measure this effect. Our calculations for the baseline case show that the leakage rate changes from 10.5% to 12.5% with no restrictions on capital movements. The same calculation for the dataset which has 8 sectors (case E) gives a corresponding change from 9.6% to 10.8%. The values reported in Table 11 show that allowing capital to be global does not greatly change the sectoral and regional contributions to the leakage. This result is in concordance with the conclusion of Burniaux and Oliveira-Martins (2000) that the degree of international capital mobility does not significantly affect the leakage.

5. CONCLUSION

Estimation of the magnitude of carbon leakage is important for policy makers because high values for leakage create a serious doubt as to the effectiveness of subglobal agreements such as the Kyoto Protocol. On the other hand, low leakage would help to attain the goal of climate stabilization. Our analysis confirms moderate values for leakage. Depending on the assumptions about fossil-fuel supply elasticities and trade substitution possibilities, the estimates for the leakage rate range from 5 to 15%.

The importance of this paper is that it provides the values for the regional and sectoral contributions toward the increase in CO_2 emissions by the non-Annex B countries resulting from the Kyoto Protocol. This information is valuable for the debate on the tax exemptions for certain industries in the Annex B countries as it reveals the most- and least-leakage contributing sectors of the economy. As expected, the carbon tax in the chemical industry makes the largest contribution (20%) to leakage in absolute terms. Introducing carbon restrictions in the iron and steel industry and in final demand also leads to a sizable increase in non-Annex B emissions. The regions where the emissions will rise the most due to the implementation of the Kyoto Protocol are China (24-32% of the total increase), and the Middle East (24-30%). The leakage is mostly induced by the actions of the European Union (36-51% of the contribution to carbon leakage based on different scenarios), the USA (28-34%), and Japan (13-18%).

It is also important to assess the relative regional and sectoral contributions. The leakage-emissions ratio (LE) and the leakage-abatement ratio (LA) provide information about relative leakage. High sectoral contribution to leakage could lead to an exemption in order to increase efficiency of global CO_2 reduction. However, the results of the modeling show that sectoral exemptions from a carbon tax are welfare-worsening.

The degree of data disaggregation is an important factor for assessing sectoral and regional contributions to leakage. Disaggregation does not substantially change the leakage rate and regional effects. In this study, it is assumed that the Kyoto Protocol is going to be implemented by all parties at the same time. Due to the path-dependency of the decomposition method, the sequence in which the policy instruments are implemented affects the results. Our study confirms the previous findings that the degree of international capital mobility does not significantly change the leakage rate. Fossil-fuel supply elasticity and Armington elasticity are much more influential factors in projecting the total world emissions of CO_2.

APPENDIX 1

THE STRUCTURE OF THE GTAP-EG MODEL BLOCKS

Figure A.1. Fossil Fuel Production

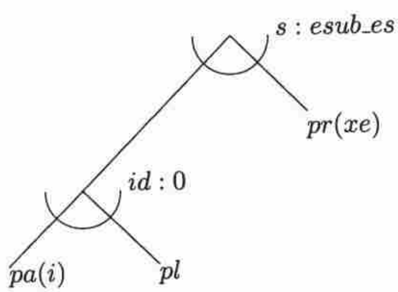


Figure A.2. Non-Fossil Fuel Production

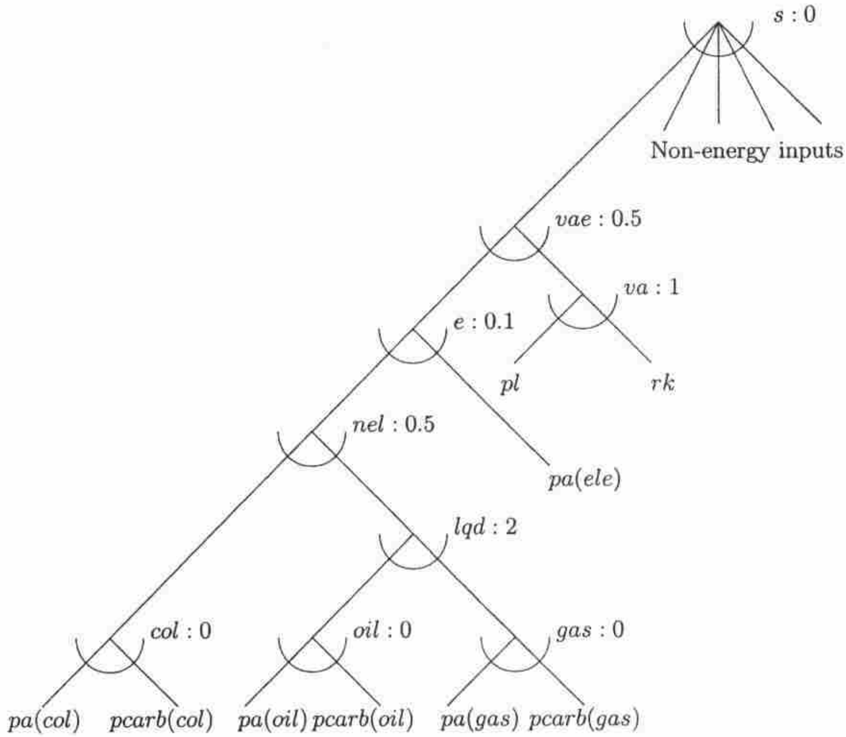


Figure A.3. Armington Aggregation

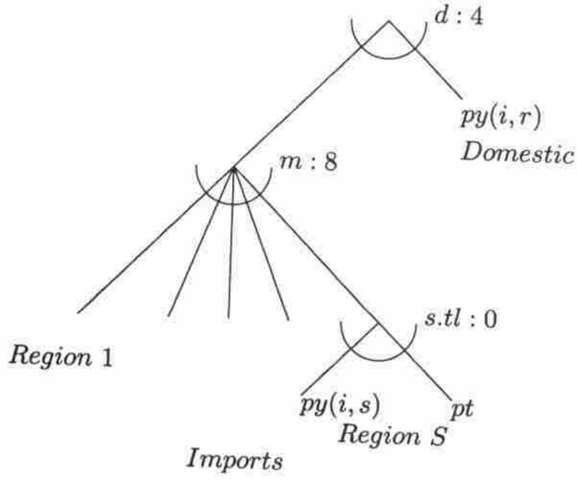
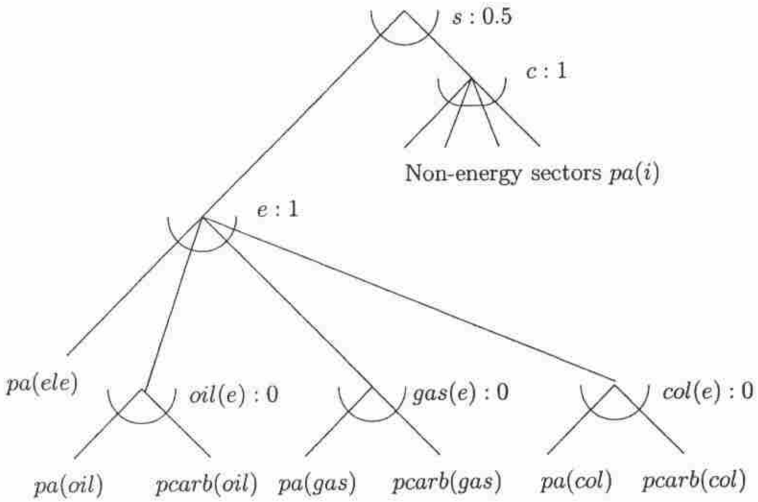


Figure A.4. Final Demand



APPENDIX 2. REGIONAL AND SECTORAL IDENTIFIERS IN THE BASE GTAP-EG DATASET

Regions:

Annex B		Non-Annex B	
USA	United States	CHN	China
CAN	Canada	IND	India
EUR	Europe	BRA	Brazil
JPN	Japan	ASI	Other Asia
OOE	Other OECD	MPC	Mexico and OPEC
FSU	Former Soviet Union	ROW	Rest of World
CEA	Central European Associates		

Sectors:

GAS	Natural gas works	FPR	Food products
ELE	Electricity and heat	PPP	Paper-pulp-print
OIL	Refined oil products	LUM	Wood and wood-products
COL	Coal	CNS	Construction
CRU	Crude oil	TWL	Textiles-wearing apparel-leather
I_S	Iron and steel industry	OMF	Other manufacturing
CRP	Chemical industry	AGR	Agricultural products
NFM	Non-ferrous metals	T_T	Trade and transport
NMM	Non-metallic minerals	SER	Commercial and public services
TRN	Transport equipment	DWE	Dwellings
OME	Other machinery	CGD	Investment composite
OMN	Mining		

APPENDIX 3. PRECISION

Two parameters can be used for estimating the precision of the decomposition method. One parameter shows the number of segments in a line integral. Another parameter represents a perturbation for numerical calculation of a derivative. From equation (6) we know that

$$\Delta Z^s = \sum_{ib} \left[\Delta X_{ib} \int_{t=0}^{t=1} \frac{\partial F}{\partial X_{ib}} dt \right] = \sum_{ib} \Delta Z_{ib}^s \tag{7}$$

where ΔZ^s is the total change in endogenous variable (representing the carbon emissions in the non-Annex B region) obtained from the model, and ΔZ_{ib}^s is the calculated by the decomposition method change in endogenous variable associated with a certain exogenous carbon tax. The precision of the method, ϵ, can be checked as the difference:

$$\varepsilon^s = \Delta Z^s - \sum_{ib} \Delta Z_{ib}^s \tag{8}$$

The precision of the method is affected by the number of segments, λ, by which the integral

$$\int_{t=1}^{t=1} \frac{\partial F}{\partial X_{ib}} dt$$

is divided for its numerical calculation. An increase in the number of segments improves the precision but increases the time of calculation. Table A.3.a shows ε for different λ.

Table A.3.a. Epsilon for Different Lambda

λ	CHN	IND	BRA	ASI	MPC	ROW
5	-0.002	-1.58E-4	-7.36E-5	-4.48E-4	-0.003	-0.001
10	-8.89E-4	-8.78E-5	-4.26E-5	-2.26E-4	-8.66E-4	-7.52E-4
15	-5.04E-4	-4.97E-5	-2.51E-5	-1.22E-4	-4.25E-4	-4.26E-4
20	-3.70E-4	-3.76E-5	-1.87E-5	-9.32E-5	-2.94E-4	-3.06E-4
25	-2.51E-4	-2.46E-5	1.20E-5	-6.43E-5	-2.11E-4	-1.98E-4
30	-1.65E-4	-1.51E-5	-7.21E-6	-4.27E-5	-1.58E-4	-1.18E-4

Another parameter, τ, shows the perturbation for calculating a partial derivative as

$$\left.\frac{\partial F}{\partial X_{ib}}\right|_t \approx \frac{F(X_{ib}^0 + t\Delta X_{ib} + \tau) - F(X_{ib}^0 + t\Delta X_{ib})}{\tau} \tag{9}$$

Table A.3.b presents the precision for various differentiation perturbations. It shows that the choice of τ is important to assure a small deviation between the model calculations and the sum of decomposed estimates for the carbon emissions.

Table A.3.b. Epsilon for Different Tau

τ	CHN	IND	BRA	ASI	MPC	ROW
1	0.009	9.52E-4	4.36E-4	0.003	0.006	0.009
0.1	0.002	1.75E-4	7.21E-5	5.03E-4	0.001	0.002
0.01	-2.25E-4	-2.56E-5	-1.17E-5	-5.48E-5	-1.45E-4	-1.30E-4
0.001	-4.79E-4	-5.07E-5	-2.20E-5	-1.24E-4	-3.41E-4	-3.54E-4
0.0001	-3.70E-4	-3.76E-5	-1.87E-5	-9.32E-5	-2.94E-4	-3.06E-4
0.00001	2.81E-4	3.98E-5	1.94E-5	1.20E-4	1.87E-4	2.47E-4

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