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Modelling Issues on Climate Change Policies

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MODELLING ISSUES
ON
CLIMATE CHANGE POLICIES
A Discussion of the
GTAP-E Model

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Abstract: After the Kyoto agreements the need has arisen to trace the implications of various international environmental strategies. In this paper, we discuss relevant modelling issues of incorporating important environmental policy measures in one of the popular applied general equilibrium models for international trade, the so-called GTAP model. Special attention is paid to an extended version, the GTAP-E model, by addressing the question how to include the widely discussed instruments of International Emission Trading, Joint Implementation, and Clean Development Mechanisms. The paper will be concluded with some policy issues.

1 Introduction

The Third Conference of Parties (CoP-3) to the FCCC held in Kyoto, 1997, led to the signature and adoption of what has become known as the Kyoto Protocol. This protocol is a result of the United Nations Framework Convention on Climate Change (UNFCCC), adopted in 1992. One of the key elements of the UNFCCC was a set of voluntary commitments to stabilize carbon emissions at 1990 levels by 2000 by the developed countries listed in Annex B of the Convention document. These countries consist dominantly of the OECD countries, the countries in Eastern Europe and the states of the former Soviet Union – e.g. the Russian Federation, the Ukraine, Belarus etc. – which are consequently referred to as the 'Annex B'-countries or 'Annex B'-Parties.

The Fourth Conference of the Parties to the UNFCCC (CoP-4) held in Buenos Aires, 1998, established deadlines for finalizing work on the Kyoto mechanisms, compliance issues and policies and measures. Many details of the Protocol remain to be worked out e.g. on the mechanisms for Annex B trading. These issues were discussed during CoP-5 held in Bonn, 1999 and it is the intention that decisions will be taken on a few of the issues during CoP-6, which will be held in The Hague, November 2000.

This paper discusses a few selected issues concerning the modelling of the Kyoto mechanisms in the GTAP-E model. These mechanisms refer to the optimal diversification of policy action over space and are therefore usually labelled 'where flexibility' mechanisms.

1) International Emission Trading (IET) concerns the transfer of 'Assigned Amounts' among Annex B Parties through the trading of greenhouse gas emission permits.

2) Joint Implementation (JI) is a mechanism for Annex B countries to achieve emission reduction credits, labeled Emission Reduction Units (ERUs) by investing in greenhouse gas abatement projects in other Annex B Parties.

3) Clean Development Mechanisms (CDM) concern ERUs transferable from Annex B Parties to non Annex B Parties.

The first two instruments can in principle reduce the total costs of emission reductions within the Annex B region, because they create the option to realize reductions in those countries where marginal abatement costs are lowest. The third instrument has also the intention to assist Parties not included in the Annex B, mainly the developing countries, in achieving sustainable development and in contributing to the ultimate objective of the Convention. From an Annex B perspective, the third instrument can be seen as an extension of this flexibility to the global level. Since costs of emission reduction are relatively low outside the Annex B area, this global flexibility should further reduce costs for Annex B Parties.

This research is part of a project of the Dutch National Research Programme on climate change. The project intends to study the effects a possible implementation of the 'where flexibility' mechanisms on international trade flows in an applied general equilibrium model.

The project team has chosen for the GTAP modelling framework. The Global Trade Analysis Project (GTAP) was established in 1992 at Purdue University. It consists of a global data base, a standard general equilibrium framework, and software for manipulating the data and implementing the standard model. GTAP is an answer to the increased demand for quantitative analysis of policy issues on a global basis. It intends to lower the cost of entry for those seeking to conduct quantitative analyses of international economic issues in an economy-wide framework. Its central ingredient is the global data base which combines detailed bilateral trade, transport and protection data characterizing linkages among regions together with individual country input-output data bases which account for intersectoral linkages within regions. GTAP intends to evolve in response to the needs of its users. As such its development has benefitted from research on policy issues that resulted from GATT Trade Policy Reviews, the Uruguay Round negotiations, and agricultural and natural resource based problems.

The detailed global data base makes GTAP particularly useful for a multiregion, applied general equilibrium analysis of global economic issues. As such it can be optimally used to study issues where international trade is a main issue, initially the area of agricultural and land-use policies, but it soon found important applications on regional trade issues and on assessing the impact of climate policies on international trade flows. Hertel and Tsigas (1997) provide three broad categories of applications, the effects of economic growth on factor markets, trade policy liberalization, and applications to resources, technology and the environment.

The organization of the paper is as follows. We provide a short description of the GTAP-E model as a framework for modelling the Kyoto Mechanisms in Section 2. Section 3 then discusses the modelling of the Kyoto mechanisms, International Emissions Trading, Joint Implementation, and Clean Development Mechanisms in GTAP-E. Finally, Section 4 offers a discussion of policy issues.

2 The GTAP-E model

This section gives a (simplified) overview of the recently developed extension of the GTAP model. The overview is based on Hertel and Tsigas (1997). For a graphical overview of the economic activities in the GTAP model, see Brockmeier (1996). We focus on the GTAP-E version of the model. GTAP-E differs from the standard model in that it adds an explicit capital-energy composite input into the production structure. For details on the modelling of this energy input into GTAP-E, see Truong (1999).

The GTAP-E model is an applied general equilibrium (AGE) model that consists of 37 industries of 20 countries in 10 composite regions. A subset of these 10 regions is referred to as the Annex B regions and is denoted by the set named 'Annex B'. Each industry is associated with the production of a traded commodity. Each commodity can be seen as domestically produced or imported with respect to each region. To allow for intra-industry trade, we assume that each domestically produced and imported commodity is substitutable, but not perfectly. This assumption is known in AGE as the Armington assumption. Commodities are assumed to be different according to the location where they are produced. Each composite region is represented by a regional household, a private household, and the producers that produce the domestic variant of each commodity.

Let us temporarily assume that taxes and tariffs are absent in the model. Then for all the agents in the model, there will be no difference between the market prices and the prices faced by the agents. We refer to market prices in the region's currency. Let $p(i,r)$ denote the market price of good i in region r.

The regional household is a hypothetical agent that collects all the income in the region. This amount of income, $M(r)$, is spent on private expenditure, $E^P(r)$, by the private household, on government expenditures, $E^G(r)$, by the government household, and on savings, $q^B(r)$ units at a price of p^B per unit, such that the region's welfare is maximized given a budget constraint,

$$M(r) = E^P(r) + E^G(r) + p^B q^B(r).$$

The region's welfare is given by a Cobb-Douglas (CD) function, which ensures that private expenditure, government expenditure, and savings represent a constant share of the region's income.

The savings of a region r consist of buying $q^B(r)$ units of the output good of a global bank sector at a market price of p^B per unit. This global bank sector is modelled as a producer whose output good is a composite investment good of which q^B units are produced at a market price of p^B per unit, based on a portfolio of the net regional investments in each region. This composite investment good is offered to the regional household in order to satisfy their regional savings demand. The net regional investments of region r equal the amount of regional investments, $q^B(r)$, net of the depreciation of the region's initial capital endowments. The amount of regional investments, $q^B(r)$, equals the total demand for capital goods in region r.

Producer i is assumed to produce commodity i in region r using a constant returns to scale production technology, which provides him with a set of production bundles, i.e. input-output combinations. In this set, he chooses the production bundle that maximizes his profits. We know from standard micro-economic theory that the constant returns to scale assumption in combination with the assumptions of perfect competition and free entry and exit on the markets makes the profit maximization problem equivalent to the producer minimizing costs per unit of output. Cost minimization then results in the optimal amount of each input. Applied General Equilibrium models such as GTAP often apply a nested structure to represent the production technology of the producer. This nested production structure is then presented in the form of a tree structure like Figure 1. Each node in the tree represents a commodity that is the aggregate of the commodities one level lower. We can see such aggregation as a production function, where the aggregate commodity is produced using the commodities one level lower. Cost minimization results in the appropriate input-output demand in each node of the production tree in Figure 1.

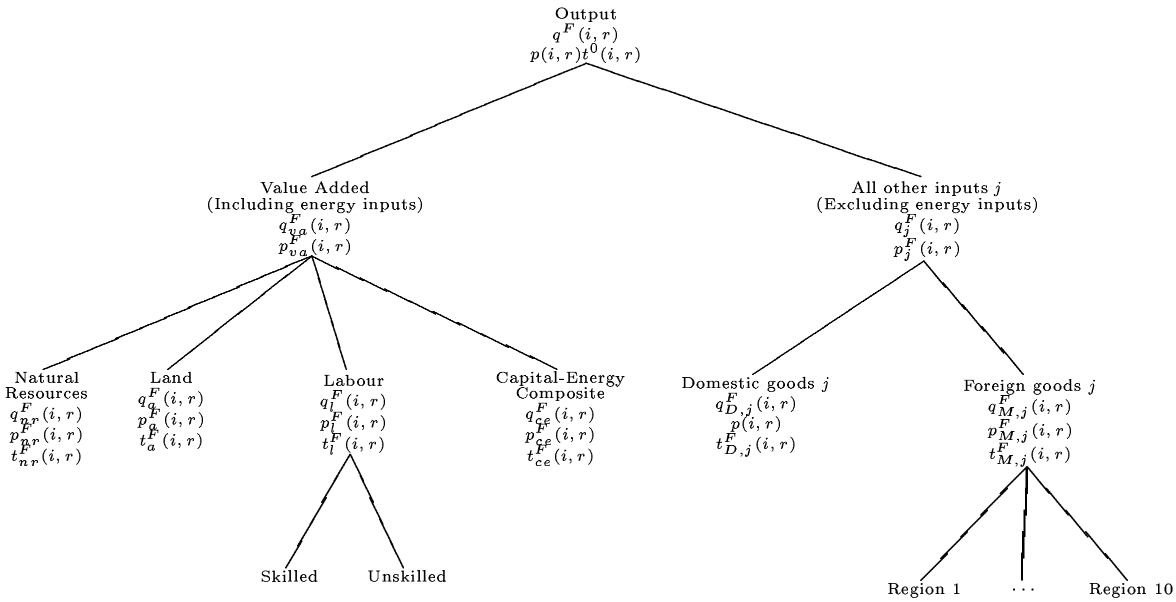

FIGURE 1: GTAP-E production structure (derived from Truong (1999)). Each node displays the appropriate value of the input-output mapping q^F, and the price mapping p^F. Some nodes also display the appropriate ad-valorem tax imposed on the underlying composite commodity.

The output of $q^F(i,r)$ units of commodity i is deaggregated in the cost minimizing amounts $q^F_{va}(i,r)$ of the composite commodity 'value added' and in $q^F_j(i,r)$ units of each composite intermediate commodity j according to a Leontief production function.

On the next level of the tree in Figure 1, $q^F_{va}(i,r)$ units of the composite commodity 'value-added' is then further deaggregated into the cost-minimizing amounts of $q^F_h(i,r)$ units of each endowment good h using a CES production function. We refer to the goods natural resources (denoted by 'nr'), land (denoted by 'a'), labour (denoted by 'l'), and the capital-energy composite (denoted by 'ce') as endowment goods. We decompose $q^F_j(i,r)$ units of each composite intermediate good j into the cost minimizing amounts of $q^F_{D,j}(i,r)$ units of the domestically produced commodity j and $q^F_{M,j}(i,r)$ units of the composite import commodity j according to a CES-production function. Commodity j can also be imported from the other countries. We aggregate these imported variations of commodity j into the composite import denoted with 'Foreign' in Figure 1.

The producer prices for the aggregate input goods of producer i in region r are given by the value of the producer price mapping p^F in each node of the production tree in Figure 1.

Marginal cost pricing determines the producer price of the good in each node of this production tree. The prices on the last nodes of the tree equal the market prices of the underlying goods.

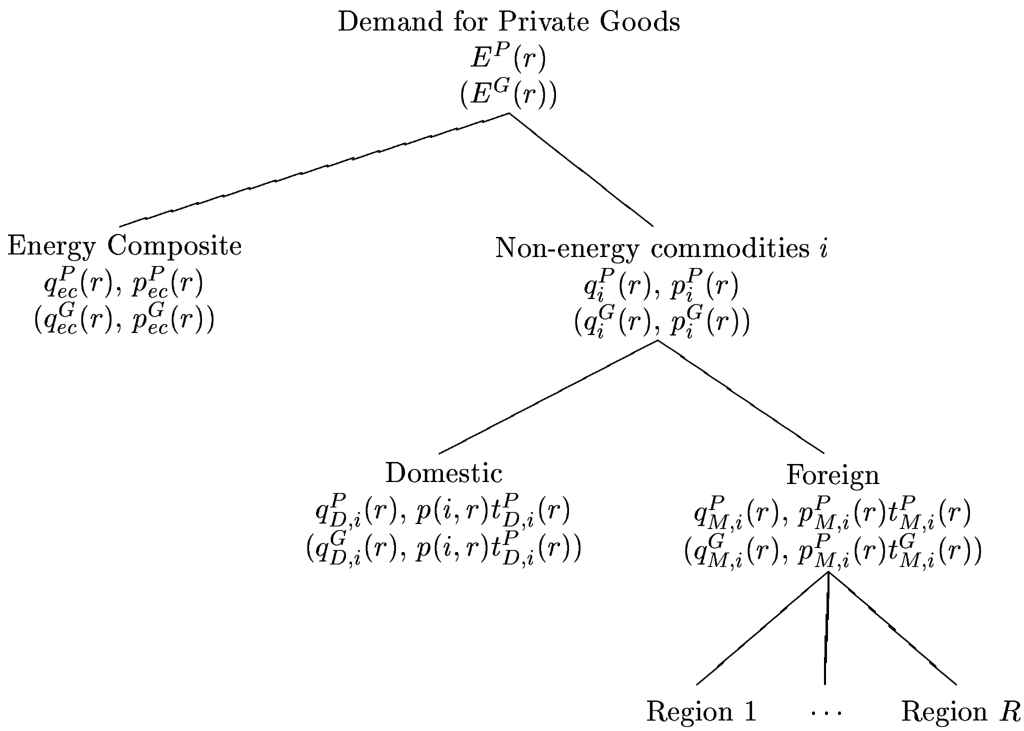

FIGURE 2: GTAP-E structure of private (government) demand (derived from Truong (1999)). Each node displays the appropriate value of the demand mapping q^P and the private household price mapping p^P of the underlying aggregate good. Some nodes also display the ad-valorem tax on the good. The variables for the government household are between brackets.

The distribution of the expenditure of the private household and the government household is given by the tree in Figure 2. The private household is assumed to spend its income on the commodities in such a way that its preferences, given by a utility function, are optimally satisfied. The consumption tree in Figure 2 displays the dual problem, namely the minimization of expenditure to obtain a certain amount of utility. The utility function is given by a function that displays constant returns to scale. Hence the consumption tree in Figure 2 is constructed similarly to the production tree in Figure 1.

In the nested structure in Figure 2, the private household spends private expenditure, $E^P(r)$, on the consumption of $q^P_{ec}(r)$ units of an energy composite at a price of $p^P_{ec}(r)$ per unit, and on $q^P_i(r)$ units of each non-energy composite i at a price $p^P_i(r)$ using a CDE function. The $q^P_i(r)$ units of the non-energy composite are decomposed into $q^P_{D,i}(r)$ units of domestically produced commodity i at the local market price $p(i,r)$ and $q^P_{M,i}(r)$ units of the composite import commodity i at a local market price of $p^P_{M,i}(r)$ per unit. This results in the demand mappings $q^P(r)$ for the private household and $q^G(r)$ of the government household in each region r. The private household prices as well as the government household prices, given by the mappings p^P and p^G respectively again follow from the 'non-positive profits' condition that results from the constant returns to scala assumption on the household's utility function.

In Figure 3 we have depicted the decomposition of the capital-energy composite in the production tree of each producer and each consumer household in the regions. The notation in this energy tree can be extended from the consumption tree using q^P (p^P) for the private household and q^G (p^G) for the governement household, and for the production tree using q^F (p^F). It decomposes the energy composite further into electric and non-electric aggregates, where the nonelectric composite is an aggregate of coal and non-coal, being again an aggregate of oil, gas, and petroleum products. The products at the bottom of the tree in Figure 3 are composites of a domestically produced variant and a composite import variant of this product.

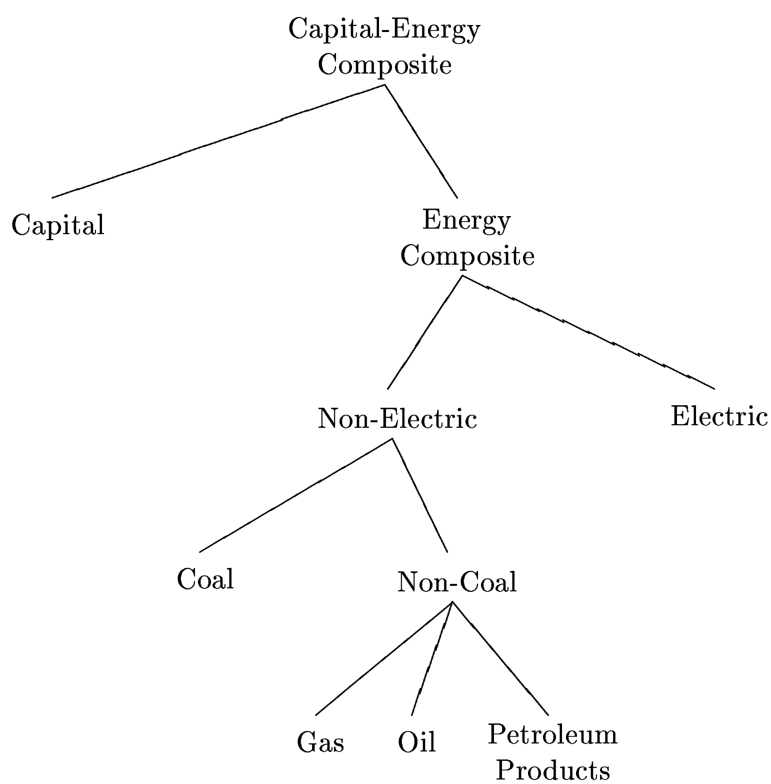

FIGURE 3: GTAP-E structure of the Capital-Energy Composite Structure (derived from Truong (1999)). For notation we extend the demand mappings q^P, q^G, and q^F and price mappings p^P, p^G, and p^F mappings over the Capital-Energy tree.

The introduction of taxes, subsidies, and tariffs into the model leads to a discrepancy between the prices that clear the markets, i.e. the market prices $p(i,r)$, of the goods i and the prices of these commodities faced by the agents. The taxes and subsidies are introduced into GTAP as net tax values. This means that a value of these variables larger than one implies the imposition of a tax on the good, while a value less than one implies a subsidy. Contrary to GTAP, we use ad-valorem taxes in our notation. Private household r pays a tax of $t^P_{D,i}(r)$ on the consumption of domestically produced commodity i and a tax of $t^P_{M,i}(r)$ on the consumption of the imported commodity i. While commodity i has a market price $p(i,r)$ on region r's local market and a market price $p^P_{M,i}(r)$ on region r's import market, the private household is faced with a price $p(i,r)t^D_{M,i}(r)$ for the domestically produced commodity i, and with a price $p^P_{M,i}(r)t^P_{M,i}(r)$ for the import composite. Similarly, government household r pays a tax $t^G_{D,i}(r)$ on the domestically produced commodity i and a tax of $t^G_{M,i}(r)$ on composite import commodity i.

Producer j in region r pays a tax of $t^F_{D,j}(i,r)$ on the input of $q^F_{D,j}(i,r)$ units of domestically produced intermediate good j, and a tax of $t^F_{M,j}(i,r)$ on the input of $q^F_{M,j}(i,r)$ units of imported intermediate good j. Region r's producer i pays a tax of $t^F_j(i,r)$ on the input of $q^F_h(i,r)$ units of primary factor service or endowment good h. Region r levies a production tax of $t^0(i,r)$ on the production of $q^F(i,r)$ units of commodity i.

The introduction of taxes, subsidies and tariffs into the GTAP model results in a discrepancy between the prices that clear the markets, the prices that are faced by the agents in the economy when they make their consumption decisions, and the prices faced abroad on the world market. To distinguish among these different prices, GTAP-E refers to market prices, agent's prices, and world market prices respectively. Brockmeier (1996) as well as Hertel and Tsigas (1997) provide an analysis of the impact of tax policies on the wedge between these prices. The revenues of these taxes accrue to the regional household, so they provide an extra income to the region.

The GTAP-model contains two global sectors, a global bank that collects all savings from the different regions and invests it back into the regions, and a transportation sector. The transportation sector produces a homogeneous transport good using the exports of any tradeable commodity as an input into its production technology. The production technology of the transportation sector is represented by a Leontief-style production function with share parameters corresponding to each flow of export between regions. These share parameters are technological coefficients. GTAP doesn't impose export taxes on the transportation of goods, so the price of the transport good is determined via the zero-profit condition on the transport production technology.

An equilibrium in this economy is defined as a set of market prices, and a set of activity levels of each producer such that the market price of each good equals the marginal costs of production, and the activity level of a production technology clears the market of the output good. The first condition is a result of the zero-profits condition that is usually made when the production technologies in the economy exhibit constant returns to scale. The second condition is known as the market clearing condition. Often, applied general equilibrium modelling adds a third condition which refers to the determination of $M(r)$ in each region r from its sources. The equilibrium conditions provide a set of (complementary) equations and variables. We refer to solving this complementary problem as the equilibrium problem. In general, applied general equilibrium models are constructed such that the equilibrium problem has a uniquely determined solution.

3 The Kyoto Mechanisms

The Kyoto Protocol as adopted during the third Conference of Parties to the Framework Convention on Climate Change (FCCC) in December 1997, defines commitments for Annex B Parties to reduce their overall greenhouse gas emissions by on average 5.2% below their 1990 levels in the five years after 2008. The commitments differ among Annex B Parties. Each Annex B Party has a different level of so-called 'Assigned Amounts' of greenhouse gas emissions. The EU committed to 8%, the USA to 7% and Japan to 6%, while Australia, Norway and Iceland committed to levels above 1990 emissions and New Zealand stabilizes emissions. Of the Central European Countries listed in Annex B, most share the EU reduction target, except for Poland (6%), Hungary (6%) and Croatia (5%). Russia and the Ukraine have only committed to a stabilization at 1990 levels. (See Bollen, Gielen, and Timmer (1999)).

Let $s^*(r)$ denote the amount of CO_2 emissions allowed for region r under the Kyoto Protocol. In GTAP-E, CO_2 emissions are a result of the use of coal, gas, oil, and petroleum products as inputs in the production processes of region r's producers or as the goods for the private and government households. For the ease of notation in this section we only consider the good 'Coal' and the composite 'Non-Coal' which is an aggregate of gas, oil, and petroleum products as described in Figure 3. The latter input goods are assumed to be a composite of the actual good itself, and a share of CO_2.

In GTAP-E, the CO_2 emissions are calculated as a share of the use of the coal and non-coal energy inputs in an equilibrium. Here we add CO_2 emissions into the model by replacing the nodes referring to the coal and non-coal input demand in Figure 3, by a two layer tree that produces the aggregate energy goods, denoted 'c-co$_2$' and 'nc-co$_2$' from pure coal respectively pure non-coal, and CO_2 in Figure 4.

We use the index h for the aggregate energy inputs cco_2 and $ncco_2$. In line with the nested production technologies introduced in the previous section, these aggregates are produced from pure 'Coal' c.q. 'Non-Coal' and 'CO_2' using a Leontief technology

$$q^F_{cco_2}(i,r) = \min\left\{\frac{q^F_{coal}(i,r)}{1-\mathrm{co_2shr}(cco_2)}, \frac{q^F_{co_2}(i,r)}{\mathrm{co_2shr}(cco_2)}\right\},$$

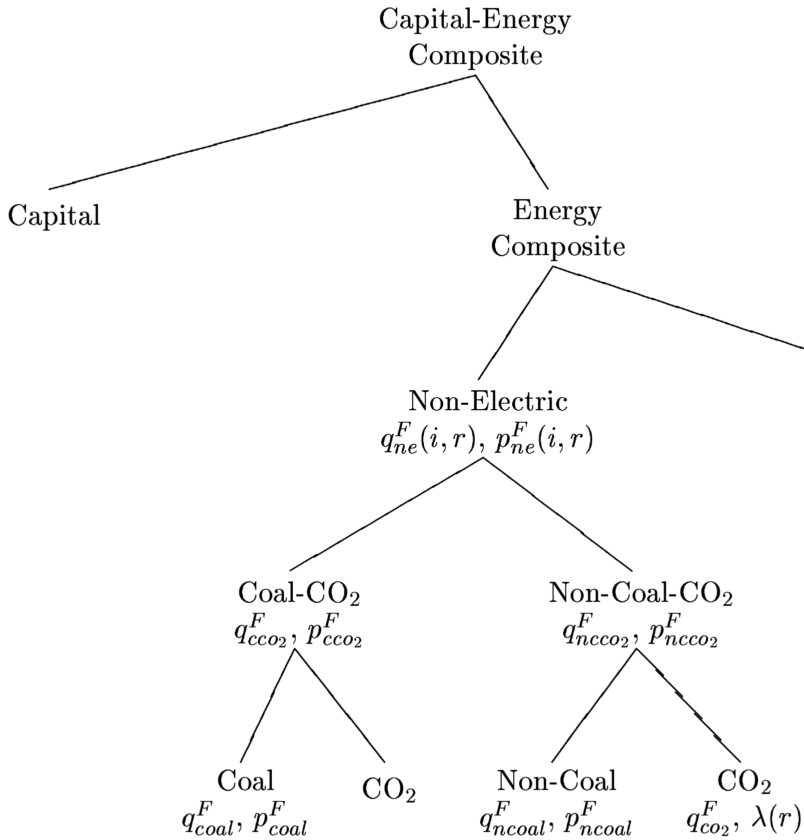

FIGURE 4: Modified GTAP-E structure of the Capital-Energy Composite Structure. The mappings q^F and p^F are extended over this tree. Only the necessary notation is added.

where $\mathrm{co_2shr}(cco_2)$ denotes the share of CO_2 in energy input cco_2. Similarly, we construct the energy input $ncco_2$ from non-coal and CO_2.

The demand functions of all production sectors in region r lead to a total input demand for CO_2 necessary for production using current technology at given prices in the economy. This total input demand for CO_2 by region r refers to region r's total emissions. According to the Kyoto Protocol, these CO_2 emissions should be brought down to $s^*(r)$ by region r, i.e.

$$\mathrm{co_2shr}(cco_2)\sum_i q^F_{cco_2}(i,r) + \mathrm{co_2shr}(ncco_2)\sum_i q^F_{ncco_2}(i,r) \leq s^*(r). \tag{1}$$

Assume that in region r there is a price $\lambda(r)$ attached to CO_2 emissions. The constant returns to scale nature of the nested production function results into a price of aggregate non-electric energy inputs cco_2 and $ncco_2$. For energy input cco_2 this becomes

$$p^F_{cco_2}(i,r) = (1 - \mathrm{co_2shr}(cco_2))p^F_{coal}(i,r) + \mathrm{co_2shr}(cco_2)\lambda(r). \tag{2}$$

Climate change policies that lead to prices and activity levels that fulfill these complementarity conditions, are *least-cost* policies or *cost-effective*. The Parties to the FCCC have introduced three new instruments under the Protocol, allowing Parties with emission limits to achieve emission reductions outside their national borders, namely International Emission Trading, Joint Implementation, and Clean Development Mechanisms. The incorporation of these policy options into GTAP-E will now be discussed.

3.1 International Emission Trading

Marketable emission permits were introduced in Dales (1968). As an alternative to effluent fees, Dales (1968) proposed a system of property rights for the management of environmental quality. Basically, property rights should be defined for environmental resources and then offered for sale to the highest bidder.

An emission permit allows its owner a certain amount of emissions. We refer to the amount of emission permits by the amount of emissions it allows. An authority can limit the amount of emissions by limiting the amount of permits. Under the Kyoto Protocol, each region r is required to limit its emissions to $s^*(r)$. Here, let region r obtain an initial endowment of emission permits that allows him $s^*(r)$ emissions. The input demand for CO_2 by region r's production sectors can then be interpreted as a demand for emission permits by this sector. We currently follow Zhang (2000) in assuming an intergovernmental emissions trading model. In such a model, governments decide not to allocate the assigned amounts to subnational entities such as the production sectors or government and private households, and retain the sole right to trade.

Intergovernmental emissions trading takes place on a government-to-government basis. In this model, (1) can then be written as region r's excess demand for emission permits,

$$\xi(r) := \mathrm{co_2shr}(cco_2)\sum_i q^F_{cco_2}(i,r) + \mathrm{co_2shr}(ncco_2)\sum_i q^F_{ncco_2}(i,r) - s^*(r).$$

Regions can cooperate to setup an emission permit trade system. Let $\mathcal{R}$ denote the set of regions that set up such a trading system. A trading system leads to a price of emission permits in each country, $\lambda(r) = \lambda(\mathcal{R})$ for each $r \in \mathcal{R}$. The permit price $\lambda(\mathcal{R})$ is such that the permit market is cleared, i.e.

$$\sum_{r\in\mathcal{R}} \xi(r) \leq 0.$$

Introducing a system of international emission permits into the economy leads to a new equilibrium with values of $\lambda(r) > 0$, $r \in \mathcal{R}$. Through (2) this has its influence on the pricing rules of the production sectors.

In a second model mentioned in Zhang (1998), governments allocate the assigned amounts to the production sectors, and authorize them to trade on the international emissions-permits market set up by the regions in $\mathcal{R}$.

Each region $r \in \mathcal{R}$ should allocate its initial endowment of emission permits, $s^*(r)$, over its production sectors. This result into a reallocation $s^*(i,r)$ of the permits such that $\sum_i s^*(i,r) = s^*(r)$. Each producer i in region $r \in \mathcal{R}$ enters the market for emission permits with an excess demand

$$\xi_i(r) = \mathrm{co_2shr}(cco_2)q^F_{cco_2}(i,r) + \mathrm{co_2shr}(ncco_2)q^F_{ncco_2}(i,r) - s^*(i,r).$$

The equilibrium condition then results into

$$\sum_{r\in\mathcal{R}}\sum_i \xi(i,r) \leq 0.$$

The issue of how the governments allocate the assigned amounts $s^*(r)$ within their countries over the production sectors, i.e. the determination of $s^*(i,r)$ is one of the key issues in the current debate on climate change. It follows from Figure 4 that the allocation of $s^*(r)$ over the production sectors determines, either directly or indirectly, the prices set equal to the marginal cost of production by the production sectors and the cost minimizing amounts of their demand for each input good. These substitution effects lead to a change in the composition of the Capital-Energy Composite as well as the constitution of value-added in the production structure of Figure 1. Through the equilibrium equation on the determination of regional income, these substitution and price effects cause the assigned amounts $s^*(i,r)$ to affect income $M(r)$, and through regional income levels, it determines the wealth of region r given by its indirect utility function. This influence of $s^*(i,r)$ makes the equilibrium in this economy dependent on the assigned emission allowances. Hence, $\mathcal{E}$ is replaced by $\mathcal{E}(s^*)$. The optimal amounts $s^*(i,r)$ should be determined such that they maximize region r's wealth. Jensen and Rasmussen (2000) not only consider to give the permits lump sum to the firms, but also consider to auction the permits over the firms, or to give them to the firms depending on their market shares.

3.2 Joint Implementation and Clean Development Mechanisms

Under conditions for qualification that remain to be defined in CoP-6, Joint Implementation would permit regions with legal obligations to control emissions in one nation party to the FCCC to satisfy all or part of those obligations by financing, directly or indirectly, emission reductions in another nation party. (see Heller (1999)). CDM investments are very similar to JI projects. The main difference between CDM and JI is that in the case of CDM projects, the host country, being a non Annex B Party, has no emission targets, while in case of JI the host country entered into the Annex B agreement.

We refer to the country where the Annex B Party is investing as the host country. CDM projects in a production sector of the host country are assumed to be carried out by its equivalent production sector of the investing Annex B Party. This Annex B Party has cleaner and more energy efficient technology, and it introduces this technology into the host country's production sector.

It is important to notice that JI and CDM are on a project basis, while the general equilibrium model refers to production sectors as the most disaggregate level. In the general equilibrium model, JI refers to emission abatement in comparable production sectors over the regions in JI coalitions.

We can distinguish three aspects to model JI/CDM into GTAP-E. First, JI/CDM introduces new technology into the host country, hence we should model technological innovation into the host country's economy, in particular with respect to energy efficiency and the use of cleaner technology. Secondly, we should adapt the investments of the host country, as some of the capital goods that are produced for the Annex B Party actually arrive into a host country. Thirdly, the Annex B Party receives credit for its investments into a host country in the form of Emission Reduction Units (ERUs).

ERUs can be defined similarly to Emission Permits, as the allowable amount of CO_2 emission. The main difference between them is that the total amount of Emission Permits is fixed and the amount and initial allocation over the regions is determined by the Kyoto Protocol, contrary to ERUs. The total amount of ERUs is unknown, nor is there an initial allocation of ERUs over the regions. ERUs are obtained by making emission saving technological investments in similar production sectors in other regions. We can model this by defining a production function for each production sector of the investing Annex B region that considers the amount of ERUs, expressed by the amount of allowable CO_2 emissions, as the output good while the capital investments by the investing Annex B region in each host region's comparable production sector refer to its input goods.

The introduction of JI/CDM provides the producer with an extra source to cover their CO_2 emissions. Apart from the tradeable emission permits, each producer can also obtain ERUs. Figure 5 illustrates the covering of a producer's emission of CO_2 using tradeable emission permits and ERUs. This figure only refers to the CO_2 part of Figure 4.

In Figure 5, production sector i in region r emits $\mathrm{co_2shr}(h)q_h^F(i,r)$ units of CO_2 caused by its input of nonelectric energy input h. This implies a demand for tradeable emission permits and ERUs, given by $\xi_h(i,r)$ and $\mathrm{ERU}_h(i,r)$ respectively, to sustain this production sector's activities. We assume that the production sector's technology is efficient with respect to emissions at the current state of technology. This technology is given by a CES production function,

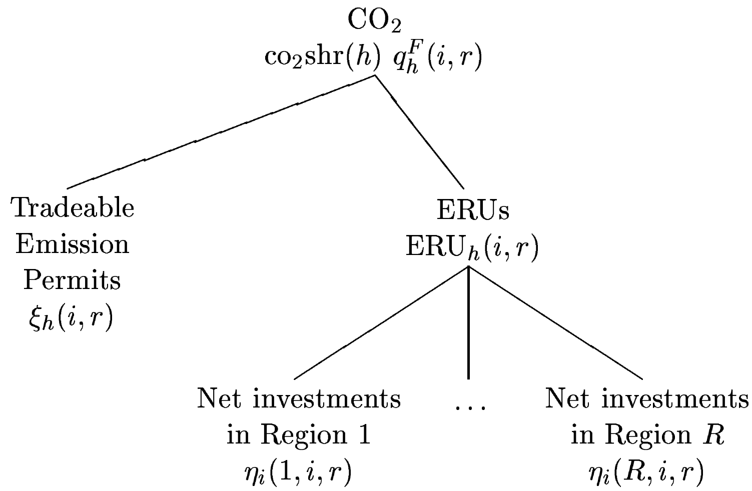

FIGURE 5: The demand for tradeable emission permits and ERUs to satisfy a producer i's demand for CO_2 emissions in region r, caused by its use of nonelectric energy input Coal ($h = cco_2$) and Non-Coal ($h = ncco_2$).

$$q^F_{co_2,h}(i,r) = \left(\nu_{hir} \xi_h^{\frac{\delta_{hir}-1}{\delta_{hir}}} + (1-\nu_{hir}) \mathrm{ERU}_h^{\frac{\delta_{hir}-1}{\delta_{hir}}} \right)^{\frac{\delta_{hir}}{\delta_{hir}-1}}, \tag{3}$$

where ν_{hir} is the share parameter of tradeable emission permits and δ_{hir} the production sector's elasticity of substitution between tradeable emission permits and ERUs. $\xi_h(i,r)$ and $\mathrm{ERU}_h(i,r)$ are obtained as the cost minimizing amounts given this technology.

The ERUs are obtained by investments in similar production sectors in regions other than r. Since other regions also make investments in this regions, we speak of net investments. In order to fulfil production sector i's demand for ERUs obtained in the previous layer of the production tree, this production sector supplies $\eta_i(\bar{r},i,r)$ units of net investments to production sector i in a host region $\bar{r}$. The allocation of net investments over these regions is given by the production function,

$$\mathrm{ERU}_h(i,r) = \left(\sum_{\bar{r}=1,\ \bar{r}\neq r}^{R} \gamma_{\bar{r}ir} \eta_i^{\frac{\phi_{hir}-1}{\phi_{hir}}} \right)^{\frac{\phi_{hir}}{\phi_{hir}-1}}$$

where $\gamma_{\bar{r}ir}$ is the share parameter of net capital investments in region $\bar{r}$ and ϕ_{hir} the production sector's elasticity of substitution. $\eta(\bar{r},i,r)$, $\bar{r} \neq r$, are obtained as the cost minimizing amounts given this technology. Investments in Annex B regions then refer to JI project while investments in developing countries refer to CDM projects.

The JI/CDM investments are used to buy capital goods which have the same efficiency with respect to CO_2 emissions as the capital goods that serve as an input into the investing production sector. Figure 5 provides the allocation of these investments over the regions. The introduction of JI/CDM leads to an extra demand for capital goods by region r in order to fulfill the demand resulting from the production sectors' JI/CDM investments in other regions $\bar{r}$. This results in region r's total supply of capital goods $\overline{q}^B(r)$ given by

$$\overline{q}^B(r) = q^B(r) + \sum_i \sum_{\bar{r},\ \bar{r} \neq r} \eta_i(\bar{r}, i, r).$$

The host production sector sees a change in the production of its capital-energy input good. This technological change might be a change in energy efficiency or in emission rates. More advanced technologies are likely to use less energy input to produce one unit of its output commodity, i.e. they are more energy efficient than older technologies. On the other hand, more advanced technologies may also be cleaner than older technologies, i.e. they cause less emissions per unit of output produced. Hence, we are faced with two types of technological progress here, namely in energy efficiency and in cleaner technology.

Acemoglu (2000) refers to the assumption on the *direction of technical change* made in almost all models of growth and capital accumulation. He distinguishes between labour-augmenting and capital-augmenting technical change with respect to a production function that has capital and labour as its inputs. Let us write the relevant production function in Figure 2 as

$$q_{ce}^F = \left(\gamma_c(i,r) (q_c^F)^{\frac{\phi_{ce}(i,r)-1}{\phi_{ce}(i,r)}} + \gamma_e(i,r) (q_e^F)^{\frac{\phi_{ce}(i,r)-1}{\phi_{ce}(i,r)}} \right)^{\frac{\phi_{ce}(i,r)}{\phi_{ce}(i,r)-1}}. \tag{4}$$

In line with Acemoglu (2000) we refer to *capital-augmenting* technical change and *energy-augmenting* technical change. Capital-augmenting technical change implies that new technologies only increase $\gamma_c(i,r)$, and do not affect $\gamma_e(i,r)$, thereby causing a shift of the isoquants parallel to the capital axis. Similarly, energy-augmenting technical change implies that new technologies only increase $\gamma_e(i,r)$, and do not affect $\gamma_c(i,r)$, thereby causing a shift of the isoquants parallel to the energy axis. Apart from changes in $\gamma_c(i,r)$ or $\gamma_e(i,r)$, technical change can also lead to a change in the technical rate of substitution of the production function. We then speak of *biased technological progress.*

JI/CDM investments change the share of energy use in the production function of the host region's production sector. This suggests that this share parameter should become dependent on the amount of investments into this production sector. Technical change refers to energy use or to emissions. The introduction of more efficient technologies into a host region r by Annex B regions $\bar{r}$ then results in a share parameter that we take as the weighted average of the share parameters in the corresponding production sectors of the Annex B regions, for example, with respect to energy use,

$$\hat{\omega}_r \gamma_e(i,r) + (1-\hat{\omega}_r) \sum_{\bar{r} \in \text{Annex B} \setminus \{r\}} \omega_{r,\bar{r}} \gamma_e(i,\bar{r}).$$

We take $\hat{\omega}_r$ to be close to 1 representing the project level of JI/CDM investments in host region r. The weights $\omega_{r,\bar{r}}$ can for example be determined by the share of region $\bar{r}$'s capital investments in host region r, i.e. let

$$\omega_{r,\bar{r}} = \left(\frac{\eta_i(r,i,\bar{r})}{\sum_{\hat{r} \in \text{Annex B} \setminus \{\bar{r}\}} \eta(h,i,\hat{r})} \right).$$

The introduction of modern technologies into development countries may well lead to the introduction of capital-energy ratios that are outside the possibilities of this country. A development country may not have the expertise to apply these new technologies efficiently, leading to the use of more, inefficient amounts of energy in order to be able to produce the required amounts of output. This refers to *technological congruence.* As a consequence, the productivity of the production sector in a developing country may turn out to be lower than expected. As a result, it is not clear whether the developing country is actually able to apply the new technology.

In (4), the energy efficiency of a production can be measured by energy-capital ratio, ${}^{q_e^F(i,r)}\!/_{q_c^F(i,r)}$. The introduction of more energy efficient technology into an Annex B host country can be done relatively smoothly compared to non Annex B hosts, in particular development regions. A non Annex B region that is confronted with modern, more energy efficient technologies might not be equiped with the proper resources to manage such technologies efficiently, i.e. there exists a lower bound, say $\alpha(i,r)$, to the energy efficiency of the production technology of non-Annex B region r's producer i,

$$\frac{q_e^F(i,r)}{q_c^F(i,r)} \geq \alpha(i,r). \tag{5}$$

Each input combination on an isoquant of (4) minimizes the costs to produce the composite capital-energy good at certain prices of the input goods. Let $c^F(p_c^F(i,r), p_e^F(i,r))$ denote the minimum costs to produce one unit of the capital-energy good. Then,

$$\begin{array}{l} p_{ce}^F = c^F(p_c^F(i,r), p_e^F(i,r)) \text{ if } q_e^F(i,r) \geq \alpha(i,r) q_c^F(i,r) \\ p_{ce}^F \geq c^F(p_c^F(i,r), p_e^F(i,r)) \text{ if } q_e^F(i,r) = \alpha(i,r) q_c^F(i,r). \end{array}$$

There exists an input price $\bar{p}_e^F(i,r)$ of energy such that (5) holds with equality. Then for energy prices $p_e^F(i,r) > \bar{p}_e^F(i,r)$, the producer is obliged to use more energy than is efficient.

4 Policy Issues

GTAP has collected a dataset of values for the variables in the model obtained over a certain period. This dataset has the form of a Social Accounting Matrix. Together with estimated values of the substitution elasticities obtained from the literature, the equilibrium problem can also be solved for its parameter values. In this way, we calibrate the equilibrium problem on the underlying dataset. We refer to the solution of the calibrated equilibrium problem as the benchmark equilibrium. Solving the calibrated equilibrium provides the underlying dataset, i.e. the benchmark equilibrium replicates the underlying dataset. In a static equilibrium model as GTAP-E, we could interpret the benchmark equilibrium as a representation of the world economy over a period of time.

This paper extends the basic GTAP-E framework to the introduction of tradeable emission permits, joint implementation, and clean development mechanisms. It then also extends the equilibrium problem with extra equations whose parameters have to be calibrated. We should then obtain data for the excess demand for tradeable emission permits, ERUs, and the JI/CDM net investments in each region by each production sector in a region to cover its emissions resulting from their input of non-electric energy inputs. Some of these data can be obtained from national and international institutions that maintain databases on e.g. CO_2 emissions in production sectors. But often, such data cannot be obtained as the climate policy options described in this paper have never been implemented. The parameters should be calibrated or chosen in such a way that the adjusted equilibrium problem again replicates the GTAP-E dataset. To this end we assume that, in the benchmark equilibrium, the price $\lambda(r)$ of CO_2 in each region r equals zero. Under this restriction, the production sectors do not take account of the CO_2 resulting from their activities.

The consequences of the introduction of tradeable emissions permits, joint implementation, and clean development mechanisms on international trade flows can be studied by relaxing the restriction on the price of CO_2 emissions. The release of the price of CO_2 emissions cause a shock on the benchmark equilibrium, and this shock results in the economy adjusting to another equilibrium, the counterfactual equilibrium.

In the counterfactual equilibrium, other prices and trade flows of the goods in the economy exist. Since CO_2 emissions now represent a cost to the production sectors, these production sectors demand cost minimizing amounts of tradeable emission permits and ERUs in order to be able to fulfill the demand for their output goods. The price $\lambda(r)$ results from the confrontation of demand and supply on the underlying permits market. The price of ERUs is, by construction, an internal price for each production sector, that results from the nonpositive profits condition in the last layer of Figure 5.

We can now study the consequences of these climate change policy instruments on the economy by comparing the obtained counterfactual with the benchmark. Since the counterfactual equilibrium immediately provides the updated values for all the variables in the model, we can easily obtain the consequences of a policy on for example the trade flows between the regions. But we can also combine the results of the counterfactual equilibrium to obtain measures that refer to the performance of a region. Quite some measures exist on this field, among them the change in gross domestic product and the so-called Hicksian Equivalent Variation. The change in gross domestic product that occurs between the two equilibria is used in applied general equilibrium modelling because policy makers are often interested in it. It is however far from perfect. Applied general equilibrium modellers prefer to use the Hicksian Equivalent Variation to measure changes in welfare caused by a policy.

Notice that the households in the GTAP-E model all have a utility function that measures their welfare. The adjustment to a counterfactual equilibrium changes the welfare of these households. The Hicksian Equivalent Variation then refers to the amount of money this household needs to remain on the benchmark welfare level. In the dual problem to this problem applied in the GTAP-E model, the Hicksian Equivalent Variation can be measured by the change in private expenditure, $E^P(r)$, and government expenditure $E^G(r)$. In case this results into a positive amount, the household is experiencing a welfare loss. The incorporation of the region as a separate household in the model, allows GTAP-E to evaluate the welfare changes to the regions as a consequence of the implementation of policies.

Jensen and Rasmussen (2000) argue that it is not only efficiency that is used as an evaluation criterium. A host of other factors such as international leakage, stranded costs, and worker displacement influence the evaluation of climate policies. International leakage occurs when environmental policies cause domestic production to be substituted with imports which may increase foreign emissions and thereby possibly offset the environmental effects of domestic climate policies. Stranded costs refer to substantial sunk capital investments associated with the current pattern of energy usage. Worker displacement likely affects the same sectors that suffer from leakage and stranded costs and is a politically sensitive subject. These factors suggest an important role for the second-order effects of climate policies on the economy in the evaluation of climate policies. In order to catch the consequences of all substitution and income effects on the international economy, we have to resort to general equilibrium models such as GTAP-E, as other types of models used in economics often only refer to one particular market thereby often ignoring second-order effects such as the factors mentioned above.

Once we have computed a counterfactual equilibrium, we may ask ourselves how sensitive a policy conclusion is to the particular values assumed for the parameters. This question refers to performing a so-called sensitivity analysis on the parameters of the model and on the policy shocks imposed on the model. A sensitivity analysis in this model results in asking oneself the question whether the welfare implications of a particular climate policy would be very different if the elasticities, δ_{hir} in the production function that determines the allocation of a production sector's CO_2 emissions over tradeable emission permits and ERUs, (3), is changed. Or, what can be the welfare implications of a reallocation of emission rights over the regions.

The realization of agreements in international climate change policy encloses many aspects varying among the various possibilities of countries to reduce emissions of greenhouse gases, the distribution of the burden of emissions reductions among succeeding generations, the impact on competitiveness and international trade, and questions of coalition forming and 'free riding'. GTAP offers a general equilibrium model with a detailed modelling of international trade flows. Its extension to the GTAP-E model adds a proper modelling of the substitution effects towards more energy efficient capital. This makes the model very suitable in particular to evaluate the potential impact of international climate change agreements on international trade, competitiveness, trade flows and investments.

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