Chapter 1
The GTAP-E: Model Description and Improvements

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Abstract A modified version of the GTAP-E model is developed in order to assess the effects of alternative climate change policies on economic and carbon emissions. We propose regional disaggregation which allows the role of major countries in economic as well as emission responses to be better defined. Sector disaggregation is closely related to international energy balances in order to calibrate the model on more realistic emission levels. An ad hoc emission intensity calibration is also implemented for better representation of sector-based emission levels. A specific analysis on substitution elasticities in the energy nests completes the proposed adjustments to the original GTAP-E model.

Keywords GTAP-E • Climate change policy • Computable general equilibrium model • Substitution elasticity • Energy balances

1.1 Introduction

In recent years, the energy-economy system has become an urgent issue to deal with due to growing concerns over climate change, the differentiation of energy sources, energy price volatility, energy supply independence and technological

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progress. Moreover, there is considerable interest in assessing the effectiveness of environmental policy measures. To this aim, applied economics makes large use of complex analytical models that attempt to capture economy-wide impacts, as much as possible.

We can divide these models into two broad categories: bottom-up and top-down models. The first describes energy demand and supply in detail and also allows the most advanced technologies to be incorporated, such as in the Markal-TIMES model (Loulou et al. 2005). On the other hand, top-down models focus on a complete representation of economic world by mapping a large set of sectors and regions. They are particularly suitable for policy evaluations at national and global level in terms of public finance, employment, terms of trade and other macro-indicators (Hourcade et al. 2006). Furthermore, after nearly two decades, modelling approaches offering a hybrid methodology began to appear in the mid-1990s (IPCC 1995).

A further important distinction in economic modelling is between computable partial equilibrium and computable general equilibrium models (hereinafter referred to as CPE and CGE models). CPE models assume fixed prices and income in the rest of the economy and include only one or few sectors whereas CGE models allow simultaneous quantification of economic trade-offs, direct effects and indirect spillovers induced by policy changes in a general equilibrium framework and in an inter-temporal and global perspective (Conrad 2001).

1.2 Bottom-Up and Top-Down Models

According to Wing (2008), bottom-up models are based on a detailed representation of the productive system as well as the demand side. Based on data on the cost and effectiveness of technologies as well as on basic resources utilisation of a country, such as energy, bottom-up models calculate the optimal mix of technological options on the basis of the cost minimisation principle subject to resource constraints by also taking into account environmental targets such as a CO_2 emission cap. This class of models can fully capture specific sectoral features by representing demand and supply complexity, especially in sectors with few market players. In contrast, their weakness is the lack of economic interconnections among markets (sectors) which would evaluate economic effects and feedbacks deriving from a general equilibrium perspective.

Top-down models, on the other hand, describe the economic system as a whole through aggregates and their interrelations in a general equilibrium framework. They put all markets in the economy in Walrasian equilibrium in terms of relative prices, given aggregate factor endowments, households' consumption behaviour (specified by their utility function) and industries' output transformation technologies (specified by their production functions). These models usually include thousands of equations and variables, both endogenous and exogenous, linked to real world data matrixes.

It is worth noting that top-down and bottom-up models often lead to divergent outcomes when evaluating the impact of policy measures. While top-down models indicate large macroeconomic costs as the consequence of a given mitigation policy, bottom-up models suggest a lower economic response in terms of price distortions, economy-wide interactions and income effects (Wilson and Swisher 1993). The reason for dissimilar results can be found in their different model structure and assumptions. In bottom-up models, the sector-specific focus generates lower costs whereas top-down models capture the costs caused by greater production costs and lower investment in other sectors. Top-down models only capture technology as the share of a given input in the intermediary consumption (usually labour, capital, energy). In CGE models, elasticities are crucial parameters representing the degree of substitutability among inputs and can vary according to different functional forms of the production function.

Recently, a new class of hybrid models has appeared. As their name suggests, these models combine a bottom-up approach – a fully detailed technological frontier representation – with the CGE model equilibrium framework, enriching their capability to represent the real world economy. Hybrid models seem to be more sensitive when assessing policy measures, suggesting higher costs than simple CGE models.

Among the various top-down CGE models, environmental CGE models have assumed special importance by extending the basic economic framework to include the use of natural resources and polluting emissions or other environmental effects associated with the production or consumption of each sector of the economy. As a result, they can be used to estimate the net economic costs or benefits of environmental policies implementing alternative policy measures (e.g. energy taxes or emission trading systems).

A typical CGE model consists of a large set of equations describing model variables and a detailed database that is consistent with the model equations. It usually manages the following types of data:

- Tables of transactions values, usually presented as input-output matrices or social account matrices (SAMs), which cover the economy of countries as a whole and distinguish a number of sectors, commodities, primary factors and types of consumers.
- Elasticity parameters: dimensionless parameters that capture behavioural response among different model actors. Elasticity values, in turn, can be divided in two types: supply and demand parameters. As an example, the supply elasticity parameter called 'factor substitution' describes the magnitude with which producers in a sector can substitute inputs (e.g. capital and energy) if their prices ratio changes.
- Tax and tariff rates for each sector and region which allow agents' prices to be distinguished from market prices.

1.3 The GTAP Model

1.3.1 An Overview

A CGE model which has recently shown outstanding growth is the GTAP model. This is part of the Global Trade Analysis Project (GTAP),[1] a global network of researchers and policymakers conducting quantitative analysis of international policy issues. The core feature of the GTAP project is a global database including input-output tables on bilateral trade flows, production, consumption and intermediate use of commodities and services as well as transport costs, tax and tariff information. Our decision to use the GTAP model was also driven by its updated and detailed database.

The GTAP model is a multiregional applied general equilibrium model, representing the global economy. In each region, a representative agent maximises utility, and private demand and production are modelled using different functional forms. Some of the most important features that distinguish the GTAP model from other CGE models are the explicit treatment of international trade and transport margins and a global banking sector which intermediates between global savings and consumption. Moreover, the model incorporates a constant-difference-of-elasticity (CDE) utility function in private household preferences. This non-homothetic functional form, unlike the usual homothetic constant elasticity of substitution (CES) function, allows for analysed simulations with large income effect.

1.3.2 The GTAP Database

The GTAP 7 database represents the world economy with 2004 as the reference year. All values are expressed in 2004 US dollars, and it covers 57 sectors in 113 regions.[2] The 57 sectors included in the GTAP 7 database are defined according to the International Standard Industry Classification (ISIC), except for the agricultural and food processing sectors, which refer to the Central Product Classification (CPC).[3]

The 113 regions (single countries or groups of countries) are defined as aggregates of 226 countries for which contributors to GTAP database provide domestic data. Table 1.1 synthesises the main sources of the GTAP database version 7.

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[1] Global Trade Analysis Project (GTAP), developed by the Center for Global Trade Analysis in Purdue University's Department of Agricultural Economics, West Lafaiette, Indiana, USA. For more information, see also https://www.gtap.agecon.purdue.edu/.

[2] The new GTAP 8 version will be available in 2012 and will allow 2004 and 2007 data to be compared.

[3] CPC was developed by the Statistical Office of the United Nations to serve as a bridge between the ISIC and other sectoral classification.

Table 1.1 The GTAP 7 database

Data source	Data description and sources
World Bank data	Macroeconomic aggregates (GDP, private consumption, government consumption and investments)
UN COMTRADE data	Trade data
OECD PSE/CSE database	Macroeconomic data (output subsidies, land-based payments, labour and capital-based payments)
WTO and 'financial report on the European Agricultural Guidance and Guarantee Fund'	Macroeconomic data (agricultural exports subsidies)
Market Access Maps (MAcMaps) developed by ITC (UNCTAD-WTO, Geneva) and CEPII (Paris)	Macroeconomic data (import tariffs)
IMF	Macroeconomic data (income and factors taxes)
Calibrated from other data sources	Behavioural information (behavioural parameters such as demand and trade elasticities)
IEA database	Model Input Energy (primary energy consumption for all 113 regions and 57 sectors included in GTAP 7 database)

Source: Narayanan et al. (2008)

In the GTAP database, I-O data may be processed in several ways and, if necessary, disaggregated as described in the GTAP database documentation.

Energy is represented by a special set of data, prepared not only to supplement data from sector generic sources but also to 'correct' I-O tables. Such an approach has been developed to fix divergences of energy data in earlier GTAP releases from International Energy Agency (IEA) data (see among others, Babiker and Rutherford 1997). With regard to energy flows, the GTAP database includes not only money value but also volume data, referring to I-O tables and international trade flows measured in millions of tons of oil equivalent (Mtoe). In particular, the energy data file contains three arrays that report the volume of energy commodities (viz. coal, natural gas, oil, oil products and electricity) purchased by firms and households and also the volume of bilateral trade in energy commodities.

The main source of energy data is the International Energy Agency 'Extended Energy Balances' (IEA EEBs onwards) for 2004. The energy balance constitutes a large array of energy flows, built using a different sectoral classification; in order to be used in the GTAP model, the energy data should be aggregated and harmonised with the rest of the database. Although the EEB classification of energy flows and products is much more detailed than the GTAP, the classification of nonenergy sectors is less detailed in EEBs. Furthermore, unlike the GTAP, IEA EEBs do not recognise gas distribution as a separate activity. For the most part, IEA EEB sectoral classifications are treated as disaggregation of the GTAP sectoral classifications. The exceptions fall into three classes. First, some of the IEA EEB sectors are discarded; these include sectors such as 'statistical differences' that represent nothing in the real world but are items of accounting convenience. Second, some of the EEB flows are coherent with GTAP classification but not in the intermediate usage block: this is true for production, exports and imports. Third, some EEB flows combine uses that must be separated in GTAP such as gas and crude oil industries, the transport industry and private consumption.

1.3.3 Model Structure

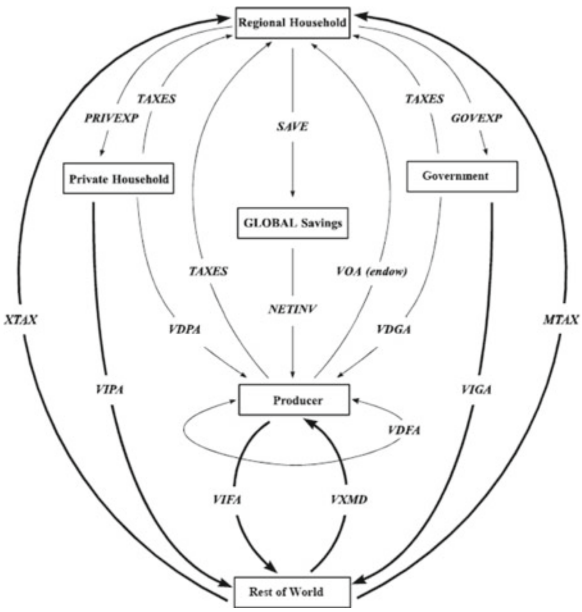
The GTAP model includes two different kinds of relationships: accounting and behavioural equations. While the first ensures the balance of receipts and expenditures for every agent in the economy, behavioural equations specify the behaviour of optimising agents (production and demand functions). Given the large number of equations in the GTAP model, providing a synthesis of the theory behind the model is not an easy task. The basic accounting relationships can be better understood with a flow chart.[4] The graphical illustration provided in Fig. 1.1 explains the basic structure of the GTAP by focusing on the accounting relationships in a multiregional open economy.

First of all, the regional household collects all income that is generated in the closed economy by each region or composite region which derives from ownership and sales of primary factors of production – capital, skilled and unskilled labour, land and natural resources. According to a Cobb-Douglas utility function, regional income is allocated across three forms of final demand (Fig. 1.1): private household expenditures (PRIVEXP), government expenditures (GOVEXP) and savings (SAVE). The flow associated with savings constitutes the input for production sector. This formulation in terms of regional household preferences is well suited to computing regional equivalent variation as an indicator of the welfare changes caused by different policy scenarios.

The GTAP production structure distinguishes between primary and intermediate factors. Among the primary factors – namely land, skilled labour, unskilled labour, capital and natural resources primary factors, the GTAP model additionally distinguishes between endowment commodities which are perfectly mobile and those that are sluggish to adjust (land and natural resources).

The production function of each sector is modelled through a 'technology tree' that contains different levels. At the top level, we find a final production nest in which primary factors and intermediate factors are combined and, at the bottom level, a value-added nest and an intermediate nest where the producer chooses the optimal mix of primary factors and intermediate inputs, respectively. It is worth mentioning that imported intermediate inputs are assumed to be separable from domestically produced intermediate inputs, following the Armington assumption (Armington 1969). Under this approach, imported intermediates are separable from domestically produced intermediate inputs: firms first decide on the sourcing of

[4] Hertel and Tsigas (1997) offers a detailed explanation of the theory behind the model, especially with regard to the derivation of the behavioural equations.



SAVE	net saving, by region
PRIVEXP	private consumption expenditure in region r
TAXES	different kind of taxes or subsidies
GOVEXP	government consumption expenditure in region r
VOA	value of commodity i output in region r at agents' prices
NETINV	regional net investment
VDPA	domestic purchases, by households, at agents' prices
VDGA	domestic purchases, by government, at agents' prices
MTAX	tax on imports on good i from source r in destination s
XTAX	tax on exports on good i from source r in destination s
VIPA	import purchases, by households, at agents' prices
VIGA	import purchases, by government, at agents' prices
VDFA	domestic purchases, by firms,at agents' prices
VIFA	import purchases, by firms, at agents' prices
VXMD	non-margin exports, at market prices

Fig. 1.1 Multiregional open economy in the GTAP model and flows denominations (Source: Brockmeier 1996)

their inputs and then, according to the resulting composite import price, determine the optimal mix of imported and domestic goods. The way in which the firm combines production factors to produce its output depends on the assumptions made on separability in the production function. Production technology is assumed to be weakly separable between primary factors of production and intermediate inputs meaning that the elasticity of substitution among any individual primary factor and intermediate input is equivalent. It is assuming this kind of separability that enables production function to be represented as a multilevel production function (technology tree): indeed, the above-mentioned common elasticity of substitution enters the fork in the inverted tree at which the primary and intermediate factors are joined.

At the top level of the technology tree, a Leontief production function operates, namely, the elasticity between value added and intermediate factors is zero, and they are combined in fixed proportions that are different for each sector. Hertel and Tsigas (1997) highlighted that the Leontief production function and the hypothesis of constant return of scale make the mix of intermediate factors independent of their prices. The technology tree is further simplified by employing the constant elasticity of substitution (CES) functional form in the value-added and intermediate nests (bottom level). Value added is then produced through a CES function of primary factors of production. Each intermediate input is in turn produced using domestic and imported components (following the Armington assumption) with the technical process described by a CES function. Finally, imported components are a mix of imports from the other regions in the global model, with the technical process again described by a CES. Under the CES functional form, the substitution possibilities within each nest are restricted to a parameter that changes from one sector to another. It should be mentioned that this CES assumption is fairly general in sectors that employ only two inputs but, when assuming that all pairwise elasticities of substitution are equal, represents quite a simplification.

Private consumer optimising behaviour is represented in the GTAP by the CDE (constant difference of elasticity) expenditure function, first proposed by Hanoch (1975). This formulation can be considered more flexible than the commonly used CES/linear expenditure system demand functions. Indeed, the CDE function has the desirable property that the resulting preferences are non-homothetic; they also allow for possible differences in income effects since marginal budget shares of individual goods can vary with income levels. CDE functions are more facilitated in their parameter requirements than functional flexible forms. Moreover, parameters of CDE demand functions can be easily calibrated using historical data on income and own price elasticities even though, with the exception of some special cases of the CDE (e.g. Cobb-Douglas functions), elasticities are not constant. On the contrary, they vary according to expenditure shares and relative prices. For this reason, elasticities are updated with iterations given by the non-linear solution procedure; such an approach also allows a mix of composite consumption of tradable commodities included in the model to be obtained, based on domestic and composite imported goods.

The static version of the GTAP model computes a linearised representation of the accounting relations described; in this form, the equations are implemented in GEMPACK language (Harrison and Pearson 2002) which solves non-linear equilibrium problems via iterations and re-linearisation. The model also provides a wide range of closure options, namely, choosing which variables are exogenous; different closures are associated with different policy experiments, exogenously imposed as shocks. Moreover, partial equilibrium closures are possible, facilitating comparisons with studies developed on partial equilibrium models.

1.4 The GTAP-E Model

Recently, growing research demands for integrated assessment of climate change issues have motivated the construction of different versions of the GTAP model and databases related, for instance, to GHG emissions, land use and biofuels.

The GTAP-E (Burniaux and Truong 2002) is an energy-environmental version of the standard GTAP model which allows for inter-fuel and inter-factor substitution in the production structure of firms and in the consumption behaviour of private households and the government sector. In addition to standard macroeconomic results, GTAP-E captures the effects arising from changes in energy-environmental policy strategies, both in terms of economic and environmental indicators.

The GTAP-E model includes modified treatment of energy demand energy-capital and inter-fuel substitution, carbon dioxide accounting, taxation and emission trading, since it has been specifically designed to be used in the context of greenhouse gases (GHG) mitigation policies. The potential of the GTAP-E in existing debate on climate change is illustrated by some illustrative simulations of the implementation of the Kyoto Protocol (among others, Burniaux and Truong 2002). It represents a top-down approach of energy policy simulation since it estimates the demand of energy inputs in terms of sectoral demand producing detailed macroeconomic projections.

The main change in the GTAP-E compared with the traditional GTAP model is the inclusion of the possibility of energy input substitution in production and consumption, allowing for a more detailed description of substitution possibilities in different energy sources. Energy substitution is incorporated in the GTAP-E model, both in the production and consumption structure. The important issue of capital-energy substitutability vs. complementarily is also explicitly considered.

1.4.1 Production Structure

In the standard GTAP model, energy inputs are treated as intermediate inputs (outside the value-added nest) whereas the GTAP-E model incorporates energy directly in the value-added nest. In this case, energy inputs are combined with capital to produce an energy-capital composite; the latter is combined with other primary inputs in a value-added-energy nest using a CES function (Fig. 1.2).

GTAP-E model incorporates energy in the value-added nest in two different steps. First, energy commodities are separated into ‘electricity’ and ‘nonelectricity’ groups, where a substitution elasticity (σ_{ENER}) operates. The following nest separates nonelectric into coal and non-coal with a specific substitution elasticity (σ_{NELY}) and non-coal into gas, oil and oil-refined products, with a specific substitution elasticity (σ_{NCOL}).

Secondly, energy composite is combined with capital to produce energy-capital composite to be incorporated in the value-added nest. This production structure can be further enriched to include biofuel production (Taheripour et al. 2007) or clean energy technologies as in the ICES model (Bosello et al. 2011).

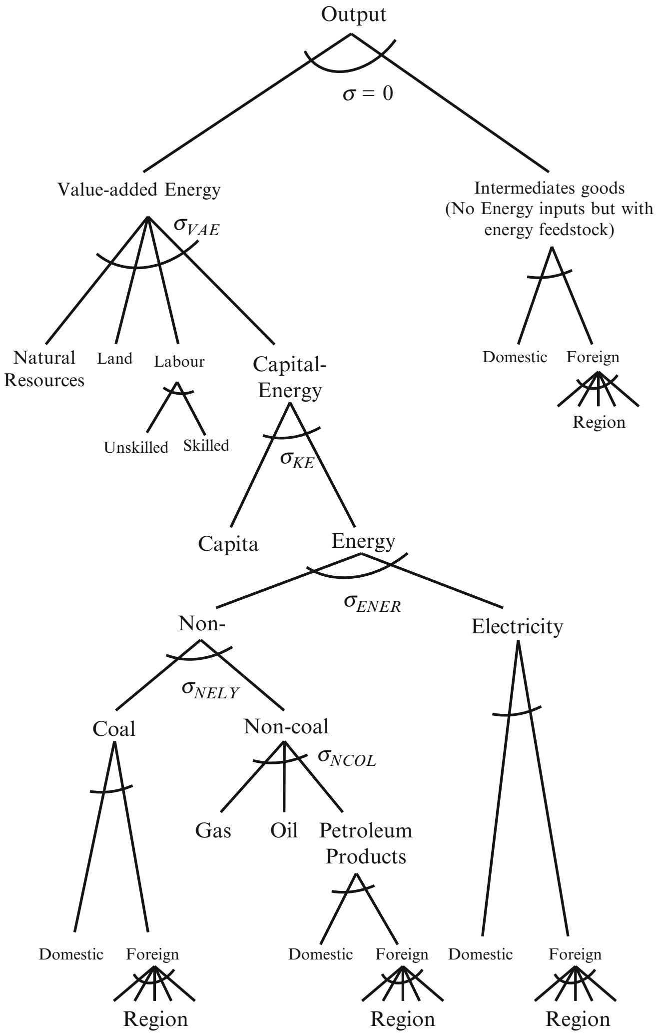


Fig. 1.2 The GTAP-E production structure

According to this approach, energy inputs are part of the endowment commodities owned by producers. Capital and energy use mainly depends on the model parameters (elasticity values) and the policy simulated.

1.4.2 Consumption Structure

As far as consumption is concerned, the GTAP-E model modifies both private and government consumption. In the standard GTAP model, private and government consumption are separated from private savings.

Government consumption has a Cobb-Douglas structure (with a substitution elasticity equal to one), where energy commodities are separated from nonenergy commodities by a nested-CES structure.

Household private consumption follows the standard GTAP model, using the constant-difference-of-elasticity (CDE) functional form previously described, but in the second-level nest, the GTAP-E model further specifies the energy composite using a CES functional form. A further significant change in the consumption structure is the possibility of adding carbon tax to private expenditure, as well as to public (government) expenditure, for goods that emit carbon dioxide when used.

1.4.3 CO_2 Emissions and Related Parameters

The GTAP-E model modifies the standard GTAP database to incorporate CO_2 emissions from fossil fuel combustion which are incorporated by region, commodity and use in million tons of carbon. Energy commodities include coal extraction (coa), crude oil (oil) extraction, natural gas extraction (gas), petroleum products (pc), electricity (ely) and gas manufacture and distribution (gdt). CO_2 emissions for electricity are equal to zero, as well as for all other nonenergy commodities.

CO_2 emission data are based on estimates from Lee (2008), properly adjusted to fit with the compatible GTAP format, which contain CO_2 combustion-based emission values from intermediate use and government and private consumption playing a key role in describing the behaviour of energy consumers in facing higher energy prices. As an example, taxes on CO_2 emissions would require energy consumers to use less-polluting energy such as natural gas instead of coal. In addition, by using detailed and reliable emission data at regional level, analyses of potential carbon leakage effects can be performed.

1.4.4 The GTAP-E Revised Version

A recent revision of the energy-environmental extension of the GTAP-E by Burniaux and Truong (2002) can be found in McDougall and Golub (2007); this is adapted to a wider range of energy-environmental policy scenarios. In particular, improvements are related to different issues such as emission data, emission trading, carbon taxation, revenue from emission trading, production structure and welfare decomposition and will be summarised below.

First, new arrays are added to the data file, showing carbon dioxide emissions by region, commodity and use. This represents another way of using the information which in the standard GTAP-E is represented as energy volume data. In particular, the database contains emissions from firms' usage of domestic and imported intermediate goods, emissions from households and government consumption of domestic and imported products.

Moreover, in order to model an emission trading system, blocs of regions trading permits among themselves are identified; a non-trading region is simply a one-region bloc. Considering the Kyoto Protocol framework where Annex-I countries may operate in an emission trading scheme, Annex-I regions constitute one single bloc whereas the remaining non-Annex regions are considered as individual blocs. To impose or relax emission constraints, a bloc-level power-of-purchases variable is defined, relating regional quota to actual emissions; when emission constraints are in force, this variable is endogenous (whereas emission quotas are exogenous) so that regional emissions and emission quotas are decoupled. When not in force, emission quotas are endogenous (whereas power-of-purchases variable is exogenous) so that regional quotas follow emissions.

An economic environment without emission constraints can be simulated by making the power of emission purchases endogenous and the real carbon tax rate exogenous.[5] In this case, there are two options for market and agents' prices: *ad valorem* tax and carbon tax. To distinguish them, a new computational level is added, including only non-carbon tax for each usage (referring to firms, private and government consumption of energy goods, domestic and imported). The model also enables carbon tax and emission trading revenues to be computed by region from all sources.

Many more intermediate levels of nesting are added in the production system, combining capital with energy at the top level. To implement this system, a new set of subproducts is defined which includes value-added-energy composite, capital-energy composite, energy composite, nonelectric energy commodities and non-coal energy commodities. Such a production system enables technological change to be simulated at every level in the nest structure. Furthermore, the set of inputs and substitution elasticities are specified with a high level of detail. A similar approach is adopted for all the other nests in the production system whether the inputs are tradable, endowments, subproducts or any combination thereof.

Due to the previous changes, welfare decomposition is subject to a double modification. First, net emission trading revenues are taken into account, and these contribute to welfare changes. Second, welfare contributions of all forms of input-saving technological changes are summed up in a single variable, including technological changes associated with the energy nests of production function.

It is worth mentioning that although GTAP-E has been specifically designed to be used in the context of GHG mitigation policies, its uses include biofuels (Banse et al. 2008; Hertel et al. 2008; Taheripour et al. 2010), induced tourism demand changes in climate change setting (Berrittella et al. 2007a) and the costs of climate mitigation policies (Nijkamp et al. 2005; Kemfert et al. 2005). The framework has also been used to examine water scarcity (Berrittella et al. 2007b) as well as the economic impacts of a rise in sea levels (Bosello et al. 2007). Lastly, Gan and Smith (2006) utilised the GTAP-E model to investigate the cost competitiveness of woody biomass for electricity production in the USA under alternative CO_2 emission targets.

[5] The real carbon tax rate is defined as the nominal tax rate deflated by the income disposition price index.

1.5 Model Improvements

1.5.1 CO_2 Emission Data Calibration

In the modified GTAP-E version (GTAP-E-M onwards) developed in this work, we introduce some changes compared with the latest version by McDougall and Golub (2007).

First of all, some changes concern the data used for this GTAP-E version since we have updated the GTAP-E dataset using the latest version of the GTAP database version 7.1 (base year 2004) as well as the latest version of the combustion-based CO_2 emission data provided by Lee (2008) for all the GTAP sectors and regions. It is worth mentioning that we introduced some adjustments to specific sectors and regions where emissions were not consistent with data provided by the main international energy agencies (EIA-DOE and IEA). Since CO_2 emission data are assigned to each region/sector on the basis of energy input volumes and emission intensity factors, we analysed country-/sector-specific data in order to understand which factors were driving these distortions the most. We found that the emission intensity factors were indeed much higher than the average for some sectors and regions leading to a substantial overestimation of the corresponding emissions reported in the official IEA data on CO_2 emissions from fossil fuel combustion. In order to reduce this bias, we replaced the emission intensity factors for those sectors and regions whose values were out of the range $-1/+1$ compared with the official IPCC emission intensity factors (Herold 2003). On the basis of these new emission intensity factors, we computed adjusted CO_2 emissions, obtaining new values for the sectors/regions characterised by outlier emission factors. The work of Lee (2008) was carefully examined; it describes the procedure implemented to calculate carbon emissions from fossil fuel combustion by users (or sectors) of all the 113 regions as covered in the GTAP 7 database. Based on the GTAP-E energy volume data, Lee followed the Tier one method proposed in the IPCC Guidelines (IPCC 2006) which is based on the different emission factors at the sector level.

When calibrating CO_2 emission levels derived from the procedure developed by Lee (2008) to assign CO_2 emissions for each region and sector, we used the contribution by Herold (2003) as a benchmark and mostly found good matching in the data although some outliers were found. The methodology we adopted to recognise outliers is as follows.

Let $\mu_{\mathrm{EF}_{ij}}$ denotes the average value of each specific i-th energy commodity and j-th sector emission factor (EF); then,

$$\left\{\mathrm{EF} < \mu_{\mathrm{EF}_{ij}} - 1;\ \mathrm{EF} > \mu_{\mathrm{EF}_{ij}} + 1\right\} \Rightarrow \ \mathrm{EF} \equiv \ \text{outlier} \tag{1.1}$$

Once we had identified all the outliers, we substituted the mean values in the outliers, instead of their original values, to obtain more consistent emission data.

Finally, we calculated new emission values by applying Eq. (1.1), and then we included the modified EF_{ij} values thus obtaining the same scheme as Lee (2008).

In order to include CO_2 emissions in the GTAP-E model, some preliminary changes had to be made to adapt data to model requirements. Since the most recent CO_2 emission database does not distinguish between domestic or imported sources, we computed these shares as proportional to the volumes of domestic production and imports, respectively. Such a choice is consistent with the methodological assumptions described in Ludena (2007) where a procedure to elaborate CO_2 emission data that are useful for the GTAP-E is described.[6]

It should be noted that emissions in our version could not account for all other GHG emissions since they only relate to fossil fuel combustion, thus providing a lower bound estimate of total emissions and abatement targets. Even if the missing emissions amounted to 15% of total GHG, the underestimation would be quite homogeneous across regions and sectors with the exception of the agricultural and chemical sectors and would not therefore influence the distributive effects of our simulations.

CO_2 emissions are produced by energy consumption by firms, government and private households. These direct emissions are taxed without discriminating between the sources of the energy products. In these sectors, domestic and imported goods are treated alike, and there are no grounds for fearing either carbon leakage or competitive disadvantage of national firms. Indirect emissions, linked to the use of nonenergy intermediate inputs, whose production involved burning fossil energy sources and CO_2 emissions, are not taken into account.

1.5.2 Updated Substitution Elasticities in the Capital-Energy Nest

It is important to point out that the GTAP-E model includes some of the most important features of existing top-down models related to energy and environment, such as those in the GREEN model (OECD 1992) and the BMR model (Babiker et al. 1997). Indeed, an important issue to consider is the structure of the substitution possibilities among alternative fuels (inter-fuel substitution) and between energy aggregate as a whole and other primary factors, such as labour and capital (fuel-factor substitution). In the GTAP-E model, substitution elasticity values between energy and capital (σ_{EK}) are crucial when determining the aggregate output related to energy price changes since technology (energy efficiency, capital turnover) has many economic implications on the production input choices; moreover, it also affects carbon emission volume, carbon permit prices and welfare. Despite its considerable importance, there are not many empirical studies on the

[6] Following McDougall and Golub (2007) and Ludena (2007), we converted emission data from Gg of CO_2, as expressed in Lee (2008), into million tons of carbon.

Table 1.2 Estimates of the elasticities of substitution between capital and energy (σ_{EK})

	USA	USA	USA	Europe	Australia
	Berndt-Wood (1975)	Kulatilaka (1980)	Pindyck (1979)	Pindyck (1979)	Truong (1985)
σ_{EK}	−3.5	−1.09	1.77	0.60	−2.95

Source: Burniaux and Truong (2002)

σ_{EK} parameter, and, in addition, available estimates often indicate nonhomogeneous results. Table 1.2 summarises some studies which attempted to estimate the partial Hicks-Allen elasticities of substitution in different regions.

Consequently, some substitution elasticities – precisely the substitution elasticity between the capital-energy composite and other endowments and the substitution elasticity between capital and energy in every nest related to the energy composite – were replaced with those proposed by Beckman and Hertel (2010), as described in Table 1.3.[7]

The Armington elasticities were also changed as suggested by Hertel et al. (2007); this specific choice allows for a better assessment of carbon leakage implications since the literature agrees on the crucial role of substitution elasticities in the quantification and geographical distribution of leakage rates (Table 1.4).

1.5.3 Model Setting and Baseline

In order to simulate different scenarios in the context of an international agreement for CO_2 emission reduction, we decided to hypothesise the implementation of the abatement targets in line with the Kyoto Protocol. To this aim, an aggregation of 21 sectors and 21 regions was identified (Tables 1.5 and 1.6).

With regard to regional aggregation, we considered a ‘full-Kyoto’ framework, with 11 Annex-I countries/regions featuring country-specific CO_2 reduction commitments. Moreover, in our disaggregation, we singled out the major emerging economies, including Brazil, China and India, as major players in post-Kyoto negotiates.

As far as sectoral aggregation is concerned, in addition to the energy sectors such as coal, crude oil, gas,[8] refined oil products and electricity, we singled out energy-intensive sectors (e.g. cement, paper, steel and aluminium) that are expected to be the main sources of carbon leakage.

Using 2004 data, a 2012 baseline was created based on the GTAP 7.1 database. To this end, we built a business as a usual scenario for emission data assuming slow

[7] For a comprehensive discussion on substitution elasticities in the energy sector, see Koetse et al. (2008) and Okagawa and Ban (2008), while Panagarya et al. (2001) and Welsch (2008) discuss the role of import demand elasticities in international trade.

[8] The gas sector in the present aggregation includes the natural gas extraction and gas manufacture and distribution sector.

Table 1.3 Elasticity of substitution values in each GTAP-E model nest

	σ_{VAE}		σ_{KE}		σ_{ENER}		σ_{ELNE}		σ_{NCOL}	
Sectors	GTAP-E-M	GTAP-E	GTAP-E-M	GTAP-E	GTAP-E-M	GTAP-E	GTAP-E-M	GTAP-E	GTAP-E-M	GTAP-E
Agriculture	0.23	0.15	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Fishing	0.20	0.15	0.25	0.50	0.16	1.00	0.00	0.07	0.25	1.00
Cattle	0.23	0.15	0.25	0.50	0.16	1.00	0.00	0.07	0.25	1.00
Forestry	0.20	0.15	0.25	0.50	0.16	1.00	0.00	0.07	0.25	1.00
Coal	0.20	3.99	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Oil	0.20	0.39	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Gas	0.65	0.35	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Oil_pcts	1.26	1.26	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00
Electricity	1.26	1.26	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Min_pcts	0.90	1.19	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Che_rub_pla	1.26	1.19	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Met_pcts	1.26	1.19	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Electr_equip	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Transp_equip	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Machinery_eq	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Motorvehicl	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Food_ind	1.12	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Tobac_bever	1.12	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Pap_pcts	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Text_leather	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Oth_manufact	1.26	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Transport	1.68	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Sea_transp	1.68	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Air_transp	1.68	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00
Services	1.35	1.36	0.25	0.50	0.16	1.00	0.50	0.07	0.25	1.00

Notes: σ_{VAE} = ESUVAMOD; σ_{KE} = ELKE; σ_{ENTER} = ENTER; σ_{NELY} = ELNE; σ_{NCOL} = ELNCOAL. See Fig. 1.2 for a graphical illustration of the GTAP-E nests and parameters

Table 1.4 Armington elasticities for domestic/imported allocation (ESUBD) and for regional allocation of imports (ESUBM)

	ESUBD		ESUBM	
Sectors	GTAP-E-M	GTAP-E	GTAP-E-M	GTAP-E
Agriculture	2.37	2.41	4.93	4.65
Fishing	1.25	2.41	2.5	4.65
Cattle	2.85	2.41	4.12	4.65
Forestry	2.5	2.41	5	4.65
Coal	3.05	2.8	6.1	5.6
Oil	2.5	30	5	30
Gas	2.5	2.8	5	5.6
Oil_pcts	2.1	1.9	4.2	3.8
Electricity	2.8	2.8	5.6	5.6
Min_pcts	2.31	2.32	3.9	4.57
Che_rub_pla	3.3	2.32	6.6	4.57
Met_pcts	3.55	2.32	7.23	4.57
Electr_equip	4.4	2.26	8.8	5.83
Transp_equip	4.3	2.26	8.6	5.83
Machinery_eq	4.05	2.26	8.1	5.83
Motorvehicl	2.8	2.26	5.6	5.83
Food_ind	2.72	2.26	5.59	5.83
Tobac_bever	1.15	2.26	2.3	5.83
Pap_pcts	3.1	2.26	6.33	5.83
Text_leather	3.77	2.26	7.57	5.83
Oth_manufact	3.75	2.26	7.5	5.83
Transport	1.9	2.26	3.8	5.83
Sea_transp	1.9	2.26	3.8	5.83
Air_transp	1.9	2.26	3.8	5.83
Services	1.91	2.26	3.8	5.83

Note: *Oil_pcts* Oil products, *Min_Pcts* Mineral products, *Che_Rub_Pla* Chemical, Rubber & Plastic, *Met_Pcts* Metal products, *Electr_equip* Electronic equipments, *Transp_equip* Transport equipments, *Machinery_eq* Machinery equipments, *Food_ind* Food industries, *Tobac_Bever* Tobacco & Beverages, *Pap_Pcts* Paper products, *Text_Leather* Textile & Leather, *Oth_Manufact* Other manufactures, *Sea_Transp* See transport, *Air_Transp* Air transport

adoption of clean technologies and economic projections to 2012 based on IMF and World Bank data on actual growth rates after the financial and economic crisis. Several steps were necessary to obtain a consistent 2012 baseline. We first updated the database to 2008, assuming population and gross domestic product as reported by the World Bank and IMF data[9] and calibrating the emissions to the most recent IEA CO_2 data. The same procedure was adopted to bring the model to 2012.

[9] In order to treat regional GDP as an exogenous variable and to shock it, regional technological progress was taken as an endogenous variable.

Table 1.5 Regional aggregation and countries

	Blocs	Countries
1	Australia	Australia
2	Belarus	Belarus
3	Brazil	Brazil
4	Canada	Canada
5	China	China
6	Croatia	Croatia
7	USA	USA
8	Swiss	Swiss
9	Turkey	Turkey
10	FSU	Former Soviet Union
11	India	India
12	Japan	Japan
13	New Zealand	New Zealand
14	Norway	Norway
15	ENEEXP	Indonesia, Malaysia, Mexico, Argentina, Bolivia, Colombia, Ecuador, Venezuela, Kazakhstan, rest of FSU, Azerbaijan, Iran Islamic Republic of, rest of Western Asia, Egypt, rest of North Africa, Nigeria, Central Africa, south central Africa, South Africa
16	EU	Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom, Bulgaria, Romania
17	Rest of Africa	Morocco, Tunisia, Senegal, rest of Western Africa, Ethiopia, Madagascar, Malawi, Mauritius, Mozambique, Tanzania, Uganda, Zambia, Zimbabwe, rest of Eastern Africa, Botswana, rest of South African Customs
18	Rest of America	Rest of North America, Chile, Paraguay, Peru, Uruguay, rest of South America, Costa Rica, Guatemala, Nicaragua, Panama, rest of Central America, Caribbean
19	Rest of Asia	Rest of Oceania, Korea, Taiwan, rest of East Asia, Cambodia, Lao People's Democratic Republic, Philippines, Singapore, Thailand, Viet Nam, rest of Southeast Asia, Bangladesh, Pakistan, Sri Lanka, Kyrgyzstan, Armenia, rest of South Asia
20	Rest of EFTA	Rest of EFTA
21	Rest of Europe	Albania, rest of Eastern Europe, rest of Europe, Georgia

Notes: We defined ENEEXP (ENergy EXPorting countries) those countries whose fuels export share absorbs more than the 10% of the total exports, according to World Bank data

In both cases, while the emission level in aggregate was correct, its distribution in terms of emission quota among regions was not satisfactory. Consequently, in the 2008 baseline, we corrected CO_2 emissions to fit the IEA data whereas in the 2012 baseline, we calibrated the CO_2 emissions to the IEA projections.[10]

[10] Emissions were swapped with technical progress using a specific closure (Altertax) that allows some data to be changed but preserves the overall consistency of the model.

Table 1.6 Regional blocs and sectoral aggregation

Regions	Sectors
Bloc Annex I	*Agriculture*
EU	Chemical, rubber, plastic
USA	Coal
Australia	Crude oil
Canada	Gas
Japan	Oil products
New Zealand	Electricity
Norway	Metal products
Swiss	Paper products
Croatia	Electrical equipment
Belarus	Food industry
FSU	Machinery equipment
Bloc non-Annex I	*Motor vehicles*
Brazil	Textile and leather
China	Transport equipment
India	Other manufacturing
Mexico	Transport
South Africa	Sea transport
Energy exporters	Air transport
Rest of Africa	Services
Rest of America	
Rest of Asia	
Rest of Europe	

1.6 Conclusions and Future Research Steps

The carbon emissions in the baseline from 2004 to 2008 computed in our version of the GTAP-E model, which includes the changes in emission intensity factors and substitution elasticities, are much more consistent with those provided by IEA. The improvement obtained is quite substantial since the standard GTAP-E model provides aggregate results that in some cases are at odds with current data. As a result, we are confident that our specification is able to provide a more accurate assessment of the potential extent of carbon leakage.[11]

It is important to point out that CO_2 emissions in the GTAP-E model, as well as the IEA data, refer to fossil fuel emissions only, excluding all other possible CO_2 equivalent emission sources. As a consequence, we recomputed the 1990 emission levels in order to get consistent CO_2 emission targets in the implementation of

[11] Robustness checks for model results to different parameters were addressed by a sensitivity analysis in which standard deviation from results in our version is rather small. More importantly, we also found that by relying on original GTAP 7.1 substitution elasticities, carbon leakage would result in overestimated values, especially due to substitution elasticity between capital and energy in the first nest under the production function.

Kyoto Protocol commitments.[12] Even if our ultimate goal is not to provide realistic CO_2 projections but to compare the economic effects of alternative policy scenarios, it is worth emphasising that Annex-I emissions in our baseline are almost identical to those proposed by IEA and reported in the most recent European Environment Agency Report.

Future steps for improving this GTAP-E version will be to model non-CO_2 GHG emissions as provided by the GTAP data source by transforming them with I-O tables into emissions subject to carbon taxation compatible with actual CO_2 emission from fossil fuel combustion. This means that non-CO_2 emissions that are now available and mainly related to final output should be transferred to consumers and firms in the form of productive inputs in order to implement a homogenous carbon tax.

Secondly, it could be helpful to shape the functioning of the emission trading system better by disentangling sectors participating or not in the carbon market and implementing an auctioning system for permits allocation rather than the current grandfathering system which seems to be less efficient.

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[12] In order to make emission levels in GTAP-E model as consistent as possible with those considered for the Kyoto targets by official IPCC documents, we first calculated the deviation between GTAP-E and IPCC emission data in 2004 and then proportionally changed the 1990 IPCC emission data in order to obtain the effective abatement efforts required by the achievement of the Kyoto Protocol targets.

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