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A COMPARISON OF COMPUTABLE GENERAL EQUILIBRIUM MODELS FOR ANALYZING CLIMATE CHANGE POLICIES

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ABSTRACT

The current unsustainable trends in greenhouse gas emissions as projected in the Second Assessment Report of the Intergovernmental Panel on Climate Change have raised considerable environmental concern among the developed countries. This concern has led to an agreement among these countries on goals and measures to reduce emissions, currently written down in the Kyoto Protocol. The realization of goals and policies proposed in this protocol will likely have major impacts on the world economy. The estimation of foreseeable effects of such policy strategies has prompted the need for an adequate modeling of this complex constellation. Hence, during the last decade several models have been developed that provide the possibility to give a quantitative assessment of the impact of climate policies on the economy. This article compares a number of important computable general equilibrium models that have been developed for this purpose in recent years. We compare different characteristics of these models, and consider the applicability of these models to particular policy strategies related to the implementation of climate change policies.

1. INTRODUCTION

The Second Assessment Report of the Intergovernmental Panel on Climate Change [1] expects that current trends in greenhouse gas emissions may cause the average global temperature to increase by 1–3.5 degrees Celcius over the next 100 years, with major consequences for sea levels and climate zones. In order to mitigate the adverse effects of climate change, IPCC recommends a stabilization of atmospheric concentration in the major greenhouse gases. It is in the light of such recommendations that international agreements, such as the Kyoto Protocol, on setting targets to emissions are achieved.

Although agreement was reached on the conditions in the Kyoto Protocol, we are still far from its implementation. The realization of agreements in international climate change policy encloses many economic aspects, varying among the various possibilities of economies to reduce emissions of greenhouse gases, the impact on competitiveness and international trade, and questions of coalition forming and "free riding."

In economic science, such policy issues are often analyzed using a mathematical model which offers a concise and consistent description of the problem as well as the underlying assumptions. The construction of economic models is often a tradeoff between tractability and complexity. A choice for tractability often results in a partial equilibrium model where only one market is studied in isolation. It uses the ceteris paribus assumption, i.e., it is assumed that everything outside this market remains constant. Partial equilibrium models give an insight into a particular problem, but second-order effects are not taken into account.

Policies to curb climate change under the Kyoto Protocol, however, have important second-order effects. One can think of the consequences of a producer's decision to invest in cleaner technology on international trade flows due to climate policies. In order to be able to catch the consequences of all such substitution and income effects on the international economy, larger models such as computable general equilibrium models are needed at the price of a higher analytical complexity.

In the literature, computable general equilibrium models have already been used regularly to assess the impact of various climate change policies on particular countries and regions. We refer to, for example, Gottinger [2] where a new class of computable general equilibrium models developed in the context of energy-economy-environmental models is employed to simulate the impact on the EU economy of internal and multilateral instruments for regulation of greenhouse gases emissions. Zhang analyzes the macroeconomic effects of limiting China's CO_2 emissions by using a computable general equilibrium model of the Chinese economy [3]. Dessus and Bussolo attempt a quantitative assessment of the interdependencies of trade liberalization and emission abatement policies with respect to Costa Rica [4]. We may also refer to Jorgenson and Wilcoxen for the modeling of U.S. environmental regulation [5].

One issue of particular interest is the impact of climate change agreements on international trade. To perform empirical analysis on this issue, a multiregional multisectoral computable general equilibrium model such as the one developed under the Global Trade Analysis Project (GTAP) at Purdue University is a suitable tool. This model offers a standard computable general equilibrium model calibrated on an up-to-date database to researchers that want to engage in quantitative analysis of international economic issues in an economy wide framework.

This article compares the GTAP-E model with a few other computable general equilibrium models that are specifically designed to address one of the aforementioned aspects of climate change policies in order to illuminate the most interesting features of modeling international climate change and international trade. Section 2 deals with general equilibrium modeling in general, while, in Section 3, we describe the GTAP-E model in particular. In Section 4 we compare the GTAP-E model with other important computable general equilibrium models often applied for analyzing climate change policies. Section 5 summarizes the article and distinguishes the characteristics of a computable general equilibrium model that are of major importance to the analysis of particular climate change policies.

2. COMPUTABLE GENERAL EQUILIBRIUM MODELING

Modern general equilibrium analysis is largely based on the Arrow-Debreu model introduced in [6]. This model can be seen as an answer to the question whether there exists an economy guided by the "invisible hand" of Adam Smith. They solved the weaknesses of the Walrasian theory of markets and validated general equilibrium theory in the mathematical explanation of existence and uniqueness of a competitive equilibrium.

The Arrow-Debreu model explicitly models the behavior of its agents, contrary to, for example, macro-economic models. The model is a pure exchange economy that distinguishes agents as either a consumer or a producer. A consumer or producer might stand for the individual consumer or producer as is often encountered in micro-economics, but might also refer to more aggregate levels. For example, a consumer might represent a certain region, while a producer might represent a certain industry. Consequentially, the consumer's preferences as well as the producer's technologies are aggregates too.

The goods are exchanged on their underlying markets and cause a price to clear it. The agents have no influence on these prices and therefore take these prices as given. Good markets are competitive. A consumer is provided with an initial endowment of each good. Given the market prices of the goods, this initial endowment offers him an income which he can exchange on the markets in order to obtain a bundle of goods that optimally satisfies his preferences. A producer is endowed with a technology that transforms a bundle of input goods into an output good. Given the market prices, a producer tries to obtain a production bundle that maximizes his profits by pursuing a demand for his input goods and a supply of his output good. A (competitive) equilibrium in this exchange economy is defined as a set of prices and an allocation of goods where the prices are such that demand equals supply on each good market, and the allocation of goods is such that each agent optimally satisfies his preferences given his budget constraint.

In the early 1970s, Scarf and others developed algorithms to compute an equilibrium in an Arrow-Debreu economy [7]. The current development in computer software and hardware offers possibilities to apply these algorithms to compute an equilibrium in, often very large, general equilibrium models applied to study policy issues. Such applied models are specific general equilibrium models. They assume that the producer's technology exhibits constant returns to scale. Under this assumption, producers can scale output up to any amount by simply replicating what they were doing before. An important consequence of this assumption is that the producer's behavior can be described by cost minimization per unit of output. Consequently, the price of each good is determined by the marginal cost to produce one unit of this good, and the supply of each good by its demand. A similar assumption is made with respect to the utility function of the consumer where the role of the cost function is taken by the consumer's expenditure function. Computable general equilibrium models often use well-behaving utility and production functions such as a constant elasticity of substitution (CES) function to circumvent technical difficulties with respect to computation and existence of an equilibrium.

Computable General Equilibrium studies collect 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 in the CES functions obtained from, for example, the literature, the equilibrium problem can also be solved for its parameter values. This procedure is known as calibration. Solving the calibrated equilibrium problem should again provide the underlying dataset. We say that this equilibrium replicates the underlying dataset. The equilibrium is referred to as the benchmark equilibrium. In a static equilibrium model, we could interpret the benchmark equilibrium as a representation of the economy over a limited period of time, assuming no change in policy. The changes caused by implementing policies into the model represent a shock on the benchmark equilibrium, and this shock results in the economy adjusting to another equilibrium, the counterfactual equilibrium.

Most computable general equilibrium models are single-period or static models. When choosing for a static general equilibrium model, one abstracts from modeling the possible adjustment of an equilibrium over time. A change in the structure of the economy makes static models loose their validity. Such models are therefore only useful for a short or medium term assessment of policies. This is of importance to the assessment of climate change policies since the impact of these policies on the climate can only be seen on the longer term, when the structure of the economy has been able to adjust itself to the use of cleaner technology. The timing and rate of technology replacement is determined by the investment policies in an economy. One of the major implications of climate change policies is therefore its impact on the investment policies in the economy. This requires a proper modeling of investment in general equilibrium models, which often makes modelers resort to dynamic general equilibrium models.

Instead of replicating the data for a single period, dynamic models generate a time path for the variables in the model, often referred to as a scenario. Policy impact assessment in dynamic models comes down to comparing a counterfactual scenario with a benchmark scenario.

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 in this field, among others 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 addressed in computable general equilibrium modeling, mainly because policy makers are often interested in it. It is, however, far from perfect. Computable general equilibrium modelers prefer to use the Hicksian Equivalent Variation to measure changes in welfare caused by a policy since it has a sound theoretical basis in welfare economics.

Under certain assumptions, there exists a uniquely determined equilibrium. We refer to Wald [8], Mas-Colell [9], and to Kehoe and Whalley [10] for details on the uniqueness of an equilibrium in these models. In order to assess the quality of an equilibrium that results from exchange, welfare economics deploys two important theorems. The first welfare theorem states that the competitive equilibrium allocation is Pareto efficient. A Pareto efficient allocation is one for which it is impossible to find another feasible allocation that makes at least one agent better off without making anyone worse off. We briefly refer to this criterion as efficiency. The second welfare theorem states that every efficient allocation can be achieved as a competitive equilibrium for an appropriate lump-sum transfer of endowments. According to the first welfare theorem, the equilibrium allocation that results from exchange given a certain distribution of the economy's endowments over the agents, is efficient. However, this equilibrium allocation may not be acceptable according to certain distributional objectives, e.g., equity considerations. An important implication of the second welfare theorem is that an exogenous force like a government may organize transfers among the agents such that these distributional objectives are reached. The main message from both welfare theorems is that the efficiency considerations can be separated from distributional considerations.

3. THE GTAP-E MODEL

The work of Scarf [7] and others on the computation of an equilibrium in system-wide economic models, has led researchers to start applying particular general equilibrium models to evaluate concrete policy impacts in real world economies. We refer to this research as computable general equilibrium modeling (CGE), although applied general equilibrium modeling is also often used. Shoven and Whalley [11] and, more recently, Ginsburgh and Keyzer [12], provide an overview of this field. General equilibrium models offer an ideal framework for appraising the effects of policy changes on resource allocation and for assessing who gains and who loses. Such policy effects are usually not well covered by empirical models.

This section gives a (simplified) overview of the GTAP model, partly based on Hertel and Tsigas [13] and Truong [14]. For a graphical overview of the economic activities in the GTAP model, see Brockmeier [15]. We focus on the GTAP-E variant of the model which differs from the standard model in that it adds an explicit energy input into the production structure. For details on the modeling of this energy input into GTAP-E, see Truong [14].

The GTAP-E model is a computable general equilibrium model that uses the GTAP-database. The GTAP-4 version of this database consists of 50 production sectors in 45 composite regions (see also McDougall et al. [16]). The production sectors in the GTAP-E model refer to the International Standard Industry Classification and comprise final goods as well as intermediate commodities. It assumes that each domestically produced and imported commodity is substitutable, but not perfectly. In GTAP-E, as is common in CGE models, this leads to distinguishing different commodities in various parts of the model, using nested expenditure and cost functions. In the context of international trade, this nesting is known as the Armington approach [17]. Commodities are then assumed to be different according to the location where they are produced, hence allowing for intra-industry trade between regions. 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.

The regional household is a hypothetical agent that collects all the income in the region. This amount of income is spent on private expenditure, on government expenditures, and on savings, such that the region's welfare is maximized given a budget constraint that is determined by the region's income. The region's welfare is given by a Cobb-Douglas function, which causes private expenditure, government expenditure, and savings to represent a constant share of the region's income.

A production sector is assumed to produce a particular output commodity in the region where he is located 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 minimizes his costs.

Computable general equilibrium models such as GTAP often apply a nested structure to represent the production technology of the producer. This nested production structure can then be presented in the form of a tree structure like

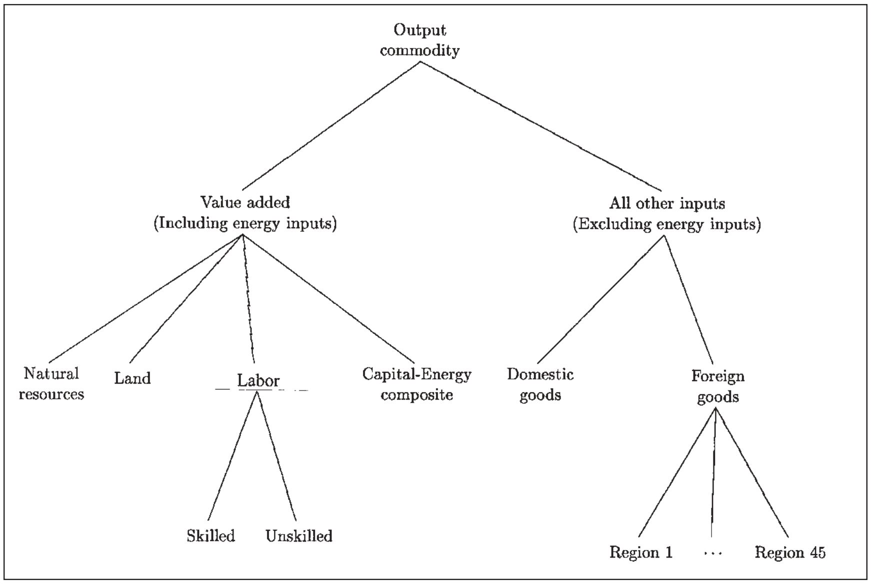

Figure 1. GTAP-E production structure (derived from Truong [14]).

Figure 1. Each node in the tree represents a commodity that is the aggregate of the commodities at a lower level. We may regard such an aggregation as a production function, where the aggregate commodity is produced using the commodities at one level lower.

The output of a commodity is disaggregated into the cost minimizing amounts of the composite commodity "value added" and in the cost minimizing amounts of each composite intermediate commodity according to a Leontief production function. On the next level of the tree in Figure 1, the amount of the composite commodity "Value-added" is then further disaggregated into the cost-minimizing amounts of each endowment good—"Natural resources," "Land," "Labor," and a "Capital-Energy"—composite, using a Constant Elasticity of Substitution production function. We decompose each composite intermediate good into the cost minimizing amounts of the domestically produced commodity and a composite of imported equivalents according to a CES-production function. Each commodity can also be imported from the other regions. We aggregate these imported varieties of a commodity into the composite import denoted by "Foreign" in Figure 1.

Notice that GTAP-E modifies the modeling of the energy input into the production technologies. The standard GTAP model, as described in Hertel and Tsigas [13], treats energy inputs in the same manner as non-energy intermediate inputs. Truong [14] cites Vinals [18] to show that the issue of energy-capital complementarity and substitutability may be a crucial one in determining the direction of the adjustment of aggregate output following energy prices. Vinals [18] constructs a simple one-sector model in which he shows that, "with no distortions, when the capital stock is given and the wage level is flexible, energy-capital substitutability is a sufficient condition for output produced to decline following an energy price decrease. Alternatively, energy-capital complementarity is a necessary condition for output produced to rise following an energy price increase." According to Vinals [18] "it is crucial for macroeconomic analysis to determine whether energy and capital are complements or substitutes."

Truong [14] proposes to shift energy from the intermediate component into the value-added component in the production technology as described in Figure 1. To this end, Truong introduces a capital-energy component in the value-added nest of production. In Figure 2 this component is a composite of capital and an energy composite. Within the nested CES function, this allows for substitution between capital and energy in the production process. GTAP-E assumes a positive elasticity of substitution between the energy composite and capital, making these

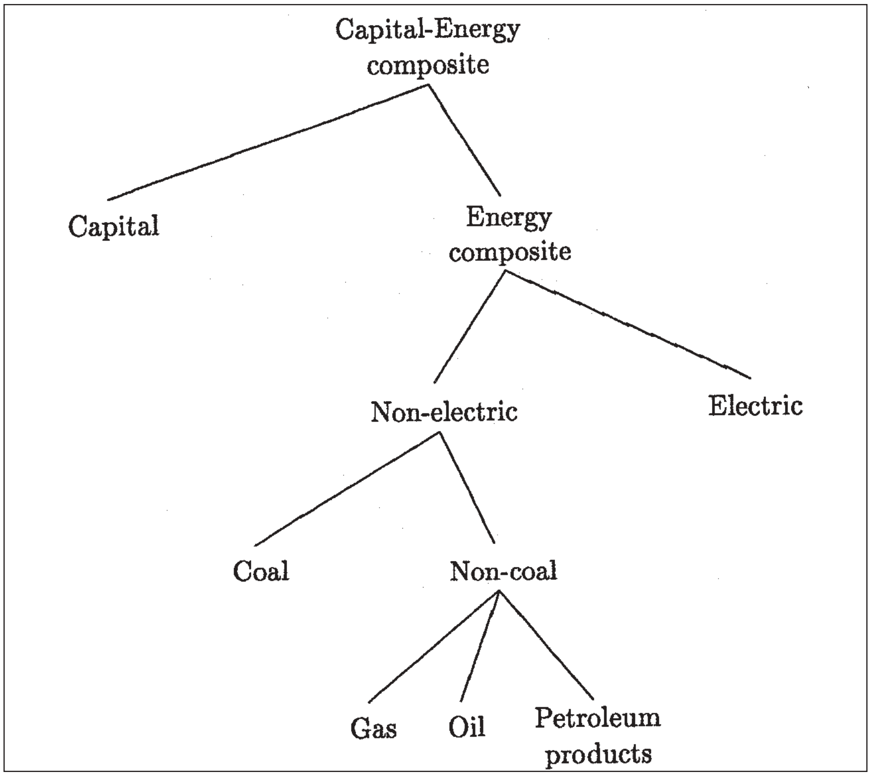

Figure 2. GTAP-E structure of the Capital-Energy composite structure (derived from Truong [14]).

goods substitutes inside this nest. The overall-substitution elasticity between capital and energy, i.e., as viewed from outside the capital-energy composite nest, may, however, still be negative.

Truong [14] also mentions that energy-capital substitutability is a long-term adjustment process. The most important changes in energy utilization depend upon changes in energy-using equipment. Equipment might change slowly, causing price shocks to have only little or no effect on demand per unit of output on the short term, while on the longer term, these price changes might well produce dramatic changes in total energy demand. A model must therefore be able to represent the flexibility in energy usage in the long run but also allow for rigidity or inflexibility in the short to medium term due to the capital constraint. Inflexibility in capital adjustment comes from technological factors such as discrete or lumpy investments, as well as adjustment costs. According to Truong, technological factors can be described by the use of so-called process models. These models describe the technologies in the energy-using or energy-producing industries, and they can be incorporated into general equilibrium models where the interactions between demand, output, and level of investment can be specified. Fully dynamic specifications of energy–economy linkages are not easily implemented and estimated.

Figure 2 decomposes the energy-composite further into electric and nonelectric aggregates, where the nonelectric composite is an aggregate of coal, gas, and petroleum products. Notice that the electric energy composite probably contains nuclear energy. The latter products are composites of their equivalents produced in each region.

GTAP-E does not include emissions into the model, but Truong [14] shows that they can be computed from the model variables. From the values obtained for the domestic consumption and imported primary energy commodities, Truong calculates the CO_2 emissions as a fixed factor per unit of these commodities.

The distribution of the expenditure of the private household and the government household is given by the tree in Figure 3. The private household is assumed to spend income on the commodities in such a way that its preferences, given by a utility function, are optimally satisfied. The consumption tree in Figure 3 displays the dual problem, namely the minimization of expenditure to obtain a certain amount of utility. It is constructed similarly to the production tree in Figure 1. Each node of this tree represents the expenditure minimizing amount of consumers of the underlying good.

In the nested structure in Figure 3, the private household spends private expenditure on the consumption of an energy composite, and on an amount of each non-energy good using a Constant Difference of Elasticities (CDE) function. the amount of the non-energy good is decomposed into an amount of a domestically produced commodity and an amount of a composite of imported equivalents at local market prices.

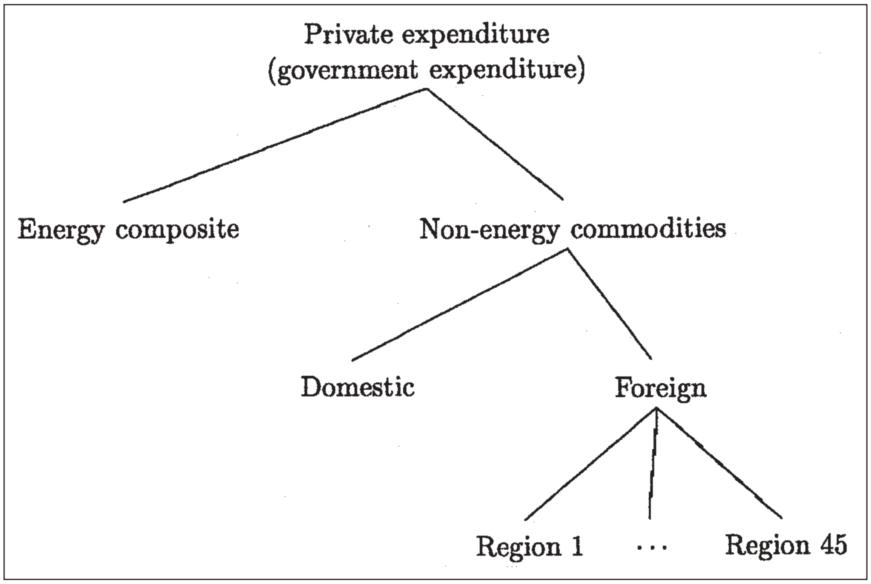

Figure 3. GTAP-E structure of private (government) demand (derived from Truong [14]).

The introduction of taxes, subsidies, and tariffs into the GTAP-E model leads to 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 or production 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 [15], as well as Hertel and Tsigas [13], 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 taxes and subsidies are introduced into GTAP-E as net tax values. 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. GTAP-E also provides the regions with the possibility to tax exports and imports. These taxes are again net taxes, and positive values refer to the levy of a tariff, while a negative value comes down to a subsidy.

The GTAP-E 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 savings of a region consist of buying an amount of the output good of a global bank sector. This global bank sector is modeled as a producer whose output good is a composite investment good which it produces from a portfolio of the net regional investments in each region. This composite investment good is offered to the regional household in order to satisfy its regional savings demand. The net regional investments of a region equal the amount of regional investments net of the depreciation of the region's initial capital endowments. The amount of regional investments equals the total demand for capital goods in this region.

The transportation sector produces a homogeneous transport good using the exports of any tradeable commodity from each region to another region as an input into its production technology. The production technology of the transportation sector is represented by a Leontief-type production function with share parameters corresponding to each flow of export commodity from a region to another region. These share parameters are technological coefficients. GTAP-E does not 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 production sector such that the market price of each good equals the marginal costs of production, and the activity level of a production sector clears the market of the output good. The first condition is a result of the zero-profit 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, computable general equilibrium models add a third condition which refers to the determination of each region's income from its sources.

The GTAP-E model, as described in this section, offers a suitable framework for analyzing the impact of different climate change policies on international trade flows. In the next section we compare this framework with other computable general equilibrium models that have often been used to address the aspects of climate change policy which we referred to in the first section. This comparison will offer us more insight into the characteristics that are of importance to properly apply computable general equilibrium modeling to address the costs of climate change policies on the world economy.

4. GTAP-E IN COMPARISON WITH OTHER CGE MODELS

The introduction of climate change policies will have important consequences for the world economy. The assessment of the impact of such climate change policies requires models that cover all aspects involved with such policies mentioned in the introduction, i.e., the impact on competitiveness and international trade, questions of coalition formation, and the various possibilities of economies to reduce greenhouse gas emissions. During the last decade several models have been developed that can assess such policies. The majority of these economic models are so-called computable general equilibrium models. This section gives an overview of some important computable general equilibrium models and compares them to GTAP-E. We have chosen these models in such a way that they cover these aspects of climate change policies, but emphasis is placed on the impact on competitiveness and international trade.

An Overview of Alternative CGE Models

In Table 1 we list a number of computable general equilibrium models next to GTAP-E, that have gained some reputation in assessing the impact of climate change policies during the last decade. Each model in this table refers to one of the aspects attached to climate change research addressed in Section 1, namely international trade, technological change, and the ecological aspects. The last two aspects of climate change are represented by only one model each, MERGE and RICE respectively. We focus on the international trade issue by choosing a number of computable general equilibrium models that differ in details addressed later in this section. In The Netherlands, the CPB Netherlands Bureau for Economic Policy Analysis developed a world model for scenario analysis, WorldScan, to analyse long-term issues in the world economy such as globalization or the emission of greenhouse gasses, or for policy analysis on trade and environmental policies. CPB [19] describes the core version of this model. WorldScan uses the GTAP database for its calibration. The GeneRal Equilibrium ENvironmental model, shortly GREEN, was developed by the Organization for Economic Cooperation and Development [20] in order to assess the economic impacts of imposing limits on carbon emissions. We refer for a description to Burmiaux et al. [21]. Lee et al. [22] provide an updated overview of the GREEN model. The Global Trade and Environmental Model (GTEM) has been developed by the Australian Department of Agriculture, Fishery and Forestry (ABARE) from their MEGABARE model [23], a dynamic model based on the GTAP model. GTEM extended MEGABARE by including an environmental part. Nordhaus and Yang [24] have developed a Regional Integrated model of Climate and the Economy, known as RICE. It is an extension of the earlier developed Dynamical Integrated model of Climate and the Economy (DICE) model which was a model that integrated a macro-economic model of the global economy with a climate system including emissions, concentrations, climate change impacts, and optimal policy [25]. The RICE model disaggregates the original DICE model from the usual single-agent approach to several countries, to be able to analyze different national strategies in climate change policies.

RICE is an alternative to the MERGE model developed in Manne et al. [26]. MERGE is a Model for Evaluating Regional and Global Effects of greenhouse gases reduction policies. It consists of three linked models which represent the major processes of interest. There is a computable general equilibrium model, GLOBAL 2200, that assesses the economy wide costs of alternative emission constraints at the regional and global level, a climate submodel that describes the relationship between man-made emissions and atmospheric concentrations and the resulting impact on temperature, and there is a damage assessment submodel to

Table 1. Description of the Different Models with Respect to Publication, Type of the Model(s), the Base Year of Calibration, and the End of the Time Period

Model	Publication	Model	Base	Period
GTAP-E	Truong [14] Hertel and Tsigas [13]	multicountry CGE	1995	—
WorldScan	CPB [19]	multicountry CGE	1995	2050
GTEM	ABARE [23]	multicountry CGE	1991	—
GREEN	Burmiaux et al. [21]	multicountry CGE	1985	2050
RICE	Nordhaus and Yang [24]	multicountry CGE	1990	2200
MERGE	Manne et al. [26]	multicountry CGE climate damage assessment	—	2200

address the impact of increasing greenhouse gas concentrations on the overall welfare. GLOBAL 2200 provides the climate submodel with energy-related emissions which is transferred by this submodel into mean temperature changes. These temperature changes, together with the realized GDP provided by GLOBAL 2200, is used by the damage assessment model to calculate market damages, i.e., reflecting categories that can be valued using prices and observed demand and supply functions, and non-market damages, i.e., reflecting categories that have no observable prices and must therefore be valued using alternative revealed preference methods.

Instead of using three submodels, the RICE model integrates these aspects into one computable general equilibrium model. Like each other computable general equilibrium model, this is a multicountry model, which implies that the world is subdivided into a set of more than two regions. The two-regions case is actually referred to as the two-country case where the world is subdivided into a specific region of interest and the rest of the world. In case the impact of world prices on the economy of the region of interest is negligible, this case refers to a small-country model. Since we are interested in international trade between different countries, only the multicountry model is of interest.

Static versus Dynamic Modeling

In Table 2 we describe the different models in our comparison according to their type, i.e., whether they are static or dynamic models. GTAP-E is a static model,

Table 2. Description of the Different Models with Respect to the Type of the Model, the Type of Expectations, and the Method of Solving the Model

Model	Type of model	Type of expectations	Method of solving
GTAP-E	static	—	—
WorldScan	dynamic	adaptive	recursive
GTEM	dynamic	adaptive	recursive
GREEN	dynamic	adaptive	recursive
RICE	dynamic	rational	intertemporal optimization
MERGE	dynamic	myopic	intertemporal optimization

and is therefore mainly suited to assess the short-term impact of climate change policy such as its influence on international trade flows. Long-term effects of implementing climate change policies such as its consequences on investments in cleaner technology and the capital stock in each region cannot properly be assessed. These investments in cleaner technology play an important role in the analysis of climate change. A proper modeling of investments is therefore of paramount importance to assess the total costs of climate change policies on society. To this end, the other models resort to a dynamic computable general equilibrium model.

A dynamic general equilibrium model includes time and time-dependent functional relationships. This inclusion of time has important impacts on the model. Consumers and producers in the model should take future developments into consideration when making their optimal decisions at each point in time. This implies the imposition of extra assumptions on how consumers and producers form their expectations over time. The literature often distinguishes myopic, adaptive, and rational expectations. Myopic expectations assume that there are no changes in the decision parameters over time. Adaptive expectations consider past experiences as important for the decisions, while rational expectations refer to forward-looking behavior of the economic subjects. Table 2 gives an overview of the type of expectations used in the various computable general equilibrium models in this article.

Models based on myopic or adaptive expectations solve a sequence of static equilibria. In Table 2, we refer to this as the recursive method or recursive dynamics. The equilibria in recursive dynamic models are connected to each other through one or more model variables. In a static model like GTAP-E, the allocation of investments over the production sectors is at the heart of the general equilibrium mechanism. The optimal allocation of endowments is determined by substitution elasticities in production functions and price elasticities in demand functions. In a dynamic model where investments become operational in a future period, current investments or allocations of capital are combined with future variable inputs. As a result, the sectoral allocation of capital also determines the demand for other inputs in the next period.

In WorldScan, dynamics are provided by investment demand, while GTEM uses capital accumulation. GTEM also uses a partial adjustment in the demography. GREEN encapsulates capital accumulation to incorporate recursive dynamics into the model, but adds a vintage structure to it. This vintage structure results in the existence of old and new capital at each point in time. Old capital consists of all the capital installed over the time preceding the current period. It is less substitutable with the other production factors and energy than new capital, and it is partially immobile between production sectors. New capital is generated by previous period's investment. New capital is assumed to be perfectly mobile and will be allocated across sectors in order to equalize its rate of return across sectors.

The RICE model assumes rational expectations. Such models cannot be solved by using the recursive method, and one has to resort to intertemporal optimization. RICE optimes global social welfare under an intertemporal budget constraint. The computable general equilibrium module of MERGE, GLOBAL 2200 optimizes the discounted utility from future consumption flows. GLOBAL 2200 uses an exogenously determined, optimal steady-state growth path of investment and consumption for solving the model. Changes in the model variables over time then have no influence on this optimal path, making the expectations assumed in MERGE, myopic.

The Level of Aggregation

The level of aggregation may refer to regions, consumers, production sectors, and production factors. Table 3 describes the specification of the six multicountry models in this article. Each model aggregates the countries in the world into a number of regions. Such aggregation depends on the focus of the study. Under the Kyoto Protocol/for example, the Annex B countries—the OECD, the countries of the Former Soviet Union, and Eastern Europe—play an important role. This would suggest that a further aggregation of the world into Annex B countries and the rest of the world is of importance when studying the consequences of climate change policies under the Kyoto Protocol. The aggregation of the world into regions is also determined by the underlying database. The aggregation of regions in the GTAP-E model shows the most disaggregate level that can be obtained from the underlying database. The level of disaggregation of the regions also determines the detail of trade flows we can study.

Table 3. Description of the Different Models with Respect to the Level of Aggregation

			Production sector		
Model	Regions	Consumer	Non-energy	Energy	Production factors
GTAP-E	USA, EU, Japan, Former Soviet Union, Indian, Net Energy Exporters, Net energy Importers, Rest of the World	Regional household	Ferrous metals, chemical rubber plastic products, other manufacturing, agriculture services	Coal, crude oil, gas, petroleum and coal products, electricity	Energy composite (=coal, gas, oil, petroleum products, electric), capital, labor composite (=skilled labor, unskilled labor), land, natural resources
WorldScan	USA, Western Europe, Rest of the OECD, Japan, Central and Eastern Europe, China, Former Soviet Union, Middle East and North Africa, Sub-Saharan Africa, Latin-America, South-East Asia, Rest of the World	Regional household	Agriculture, raw materials, intermediate goods, capital goods, consumer goods, trade and transport services	Coal, oil, gas	Capital, fixed factor, labor composite (high-skilled labor, low-skilled labor)
GTEM	Australia, New Zealand, United States, Canada, Japan, European Union, South Korea, China, China Taipei, Indonesia, Other ASEAN, India, Mexico, Brazil, Rest of America, Former Soviet Union, Eastern Europe, Rest of the World	Regional household differentiated in terms of age-composition	Chemicals, iron and steel, non-ferrous metals, fabricated metal products, primary agriculture, processed agriculture, resources processing, manufacturing services	Technology bundle (solar, hydro, geothermal and other; coal fired; nuclear; gas fired; and oil fired); coal, oil, natural gas, other minerals, petroleum products, electricity	Capital, land, labor, sector specific natural resources (coal, gas, petroleum, oil)

GREEN	USA, EU, Rest of the OECD, Japan, Central and Eastern Europe, China, Former Soviet Union, India, Brazil, Dynamic Asian Economies, Major Energy Exporting countries, Rest of the World	Regional household	Agriculture, energy intensive industries, other industries and services	Oil, crude oil, natural gas, refined petroleum products, electricity (incl. gas and water), 7 energy backstop substitutes	Capital (new and old), labor, sector specific factors (land, coal, crude-oil, natural gas, electric capital); putty-semi putty technology
RICE	USA, EU, Japan, Former Soviet Union, China, Rest of the World ((i) India, Brazilia, Indonesia; (ii) 11 large countries; (iii) 137 small countries	Regional household	One aggregated output with different input factors		Capital, labor, and technology
MERGE	USA, other OECD nations, Former Soviet Union, China, ROW	Regional household	One aggregated output with different input factors		Energy, non-energy, capital, and labor

Each region can also be represented by a single decision maker as in MERGE. The single decision maker in MERGE is a consumer-producer aggregate who determines his levels of consumption and production that optimize his welfare under the constraint imposed by the economy. RICE uses the decision makers that represent the different regions as players that can choose among three types of strategies to face the implementation of climate change policies: market policies, cooperative policies, and noncooperative policies. Each of these strategies leads to a different payoff in the form of welfare for each region.

GREEN, GTEM, and WorldScan provide more detail by introducing a representative consumer household, the producers representing each production sector in the region, and a regional government into the model. GTEM even distinguishes more detail by differentiating the consumer household in terms of age composition. Each of these agents behaves according to some maximization principle. The representative consumer household chooses consumption levels of each available good and labor supply in order to maximize its welfare given his budget constraint, while each producer chooses his input and output combination such that his profits are maximized given his production technology. The government household can be modeled as a special kind of consumer household providing government consumption or, simpler, just to balance budgets. All agents are assumed to be price takers, so they determine their optimal demand and supply levels given the prices in the economy. The prices are assumed to be such that they clear the markets. Markets are assumed to be competitive. This setup of computable general equilibrium models allows an assessment of the consequences of climate change policies on the welfare of consumers in each region. GTAP-E provides an extension of this idea by introducing a regional household that can be seen to aggregate the region's other households, which allows also an assessment of the consequences of climate change policies on the region as a whole.

Also, the goods in the economy are aggregated. A computable general equilibrium model assumes that each aggregate good can by seen as the unique output good of a production sector. The production of energy goods play an important role as it is the most determinant factor of CO_2 emissions. In Table 3, we have therefore split up the production sectors into energy and non-energy production sectors. Most energy intensive production sectors use an electricity aggregate and a non-electricity aggregate as energy inputs. The electricity aggregate is assumed to be relatively clean with respect to CO_2 emissions, contrary to the non-electric aggregate. Nuclear energy, which gives no CO_2 emissions, is a constituent of the electric aggregate. This prevents a complete switch toward nuclear energy in the case of a significant price rise of CO_2 intensive energy sources. GTAP-E and WorldScan, for example, decompose non-electric energy into coal, crude oil, gas, and petroleum products. These energy sources are responsible for a producer's CO_2 emissions.

The Modeling of International Trade

Each region produces the same set of goods. Classical trade theories then predict a process toward specialization in the countries. This is the standard Heckscher-Ohlin-Samuelson assumption. In order to prevent specialization, most computable general equilibrium models, such as GTAP, WorldScan, and GREEN, assume that the regional variants of each good are incomplete substitutes. Cross elasticities between variants of the same goods are then finite. Consequently, with respect to each region, there exists a domestically produced variant of each good and an imported variant, which most models assume to be an aggregate good of all the foreign variants of this good. The Armington approach on international trade often leads to a nested structure of the expenditure function of the consumer households and cost function of the production sectors. Models choose different specifications to include the Armington approach into the model. Table 4 provides an overview of the specifications for the consumer's expenditure function and the production sectors' cost functions in each model.

It is interesting to note that a dynamic computable general equilibrium model such as WorldScan assumes that goods become perfect substitutes in the long run, i.e., conforming to the standard Heckscher-Ohlin assumption. Under the

Table 4. Description of the Different Models with Respect to the Specification of Utility, Expenditure, and Cost Functions

Model	Consumer household	Production sector
GTAP-E	Nested CD utility function CDE expenditure function Extended linear expenditure savings function Keller government expenditure function	Nested CES three level
WorldScan	CD discrete time utility function	Nested CES two level
GTEM	Nested CES/CD discrete utility function	Nested CES two level
GREEN	Discrete time utility function with extended linear expenditure function	Nested CES four level
RICE	Constant relative risk-aversion Discrete time utility function	—
MERGE	Logarithmic discrete time utility function	Nested linear

Armington approach, countries have a fixed product mix; however, according to WorldScan, the composition of goods changes gradually over time. Modern trade theories of monopolistic competition consider the product mix to be endogenous. WorldScan follows this approach by changing the static Armington utility function into a dynamic one, describing temporary brand-loyalty. Countries can gain market share by temporarily offering their products at a lower price than their competitors. Once market shares are conquered, brand loyalty is established and gradually prices return to the competitor's prices.

The other extreme is taken by MERGE and RICE that only consider consumption, c.q., output, as an aggregate. With respect to international trade, these models offer much less detail than the aforementioned CGE models. In these models, the regions should be interpreted as agents who trade in homogeneous goods in an international goods market. This results in a market clearing price with respect to the good.

Under the Armington approach, each region contains a regional market for its goods as well as regional markets for the composite import alternatives, which determine the region's prices for all these goods. In the GTAP-E, WorldScan, and GREEN models, there exists a regional labor market which causes a difference in wage rates over the regions. Labor in these models is not mobile over the regions, but is over the region's production sectors. GTAP and WorldScan assume the existence of an international capital market, which makes capital mobile over the world, and results in a globally determined rent rate. GREEN takes another view when introducing vintages of old and new capital. The market for new vintage capital is a regional market resulting in a single regionwide rate of return, while there only exists a sector specific old vintage capital market which causes the rate of return on old vintage capital to vary over the production sectors.

The Modeling of Energy and Carbon Emission

Carbon emissions are primarily associated with the use of energy in production processes. Climate change processes are therefore often directed to the use of energy sources in production. Such policies then lead to important effects on the economy. It is through the effects on emissions that climate itself is affected. A complete assessment of the impact of climate change policies on the economy, either directly through its impact on energy use or indirectly through the impact of an improved climate, requires a detailed modeling of energy use and carbon emissions in a computational general equilibrium model.

As Gottinger writes, energy is an ubiquitous input in production [2]. Different energy sources are substitutable for each other, and in the aggregate, in the long run with other inputs such as capital, labor, land, and materials. Policy instruments designed to alter energy patterns may therefore be expected also to have an impact on the use of other inputs and carry over to the whole economy through inter-industry linkages and changes in factor incomes. If the economy is open, there are likely to be changes in trading patterns as well.

GTAP-E applies a nested production function which allows for the substitutability among different kinds of energy sources, inter-energy substitution, and between energy and capital, capital-energy substitution (see Figure 1, which contains the nested production function referring to the capital-energy input of Figure 2). The nested production function where one of the nests refers to a capital-energy aggregate allows capital and energy to be either substitutes or complements depending on the production function's parameters (see [14] and Section 3 of this article). This nested structure of the production function corresponds to the approach taken by GREEN, which adds a backstop-technology. WorldScan does not provide detailed information on energy consumption in each production sector and it regards energy as an intermediary input. It may therefore be less appropriate for analyzing interfuel substitution. As Mooij et al. noted [27], the model is likely to produce biased results for CO_2 emissions when implementing climate policies.

In GTEM, the consumption of carbon-based fuels is derived from a "technology bundle"-approach which, theoretically, allows for substitution among alternative technologies instead of the more traditional concept of substitution between alternative energy and non-energy inputs. A technology bundle is a smooth production function with the output quantities of each technology as its inputs. In this approach, the gross output of a production sector is a Leontief function of such a technology bundle and commodities, for example oil and capital. This approach may be theoretically appealing because it offers a more realistic description of the constraining factors in the energy producing and energy using industries, but Truong raises some questions with respect to the practical implementation of this approach [14].

MERGE and RICE provide a more detailed modeling of climate change and its interactions with the economy. MERGE also includes the emission of other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O). The climate submodel then uses information on these emissions to calculate temperature changes. The linkage between temperature changes and its results on the economy is provided by a damage assessment model. RICE combines these different models into one.

CONCLUSIONS

This article distinguishes three major aspects involved with climate research, namely the impact of climate policies on international trade flows, strategic issues regarding the timing of climate policies, and the interaction between economy and climate, i.e., an ecological issue. We selected a number of computable general equilibrium models, each of them with a particular set of characteristics that make them particularly suitable to address one of these issues. In Section 4 we gave an overview of the models according to these characteristics.

Models that are suitable to address the first issue primarily focus on the economic part of climate change modeling, and restrict the modeling of energy to a minimum level sufficient to enable the modeler to attach a price on energy use, often in the form of a tax. Such modeling will not do when addressing the third issue of climate change modeling, the interaction between economy and ecology.

The modeling of the interaction between economy and ecology requires more information on the impact of a change in CO_2 emissions on the climate itself and on the impact of a change in the climate on the welfare in the economy. MERGE offers two submodels that describe the impact of a change in CO_2 emissions on the climate itself and the impact of climate change on the welfare in the economy. The lack of such information in the GTAP-E model makes the latter model unsuitable for a complete assessment of the impact of climate change on the economy.

The implementation of climate change policies under the Kyoto Protocol also has a short term impact on international trade flows. These effects can be captured by a static computable general equilibrium model such as GTAP-E. In order to provide a complete assessment of climate change policies, one should, however, take the long-term effects into account. On the longer term, the structure of the economy will have been adjusted to incorporate more energy efficient and cleaner technologies. For an assessment of these effects of climate change policies, a static model as GTAP-E no longer suffices and one has to resort to models with a dynamic setup, such as the other models mentioned in this article. WorldScan is such a dynamic model. It also incorporates the GTAP database, so it is able to asses the impact on international trade flows. WorldScan however lacks the details in energy modeling of GTAP-E.

The Kyoto Protocol also allows its participants to choose how they will coordinate their efforts to reduce emissions under the levels subjected to in the protocol, i.e., whether they implement it on a stand-alone basis, or jointly with other regions. This implies the presence of strategic behavior, coalition formation, and negotiations with respect to the implementation within coalitions. RICE is a multiregional model that is geared to assess the outcome of such strategic behavior, but it lacks the details of WorldScan and GTAP-E.

The choice for a particular computable general equilibrium model is mainly determined by the policies one intends to study. Implementing climate change policies will lead to huge costs for an economy. The high costs associated with combating the adverse consequences of climate change have led to intense debates in academic and policy domains that address the optimal formulation of policies. OECD, [20] basically distinguishes four types of flexibilities that provide countries with possibilities to influence total discounted costs by diversifying reduction activities over space, time, instruments or types of emissions (see also [28]).

The Kyoto Protocol incorporates a variety of provisions for cooperative implementation mechanisms that reflect the guiding principles that “policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost.” Marginal costs of reduction vary substantially between regions or countries. These costs tend to be relatively low in non-OECD countries. From an economic optimality point of view, reductions should be achieved in countries with the lowest abatement costs. This refers to the optimal diversification of policy over space, labeled “where flexibility.” The Kyoto Protocol mentions Emission Trading, Joint Implementation, and the Clean Development Mechanism as instruments to operationalize this type of flexibility. The models that address the first aspect involved with climate change mainly refer to “where flexibility” policies.

The latter models can also play an important role in assessing the impact of policies that refer to “how flexibility.” “How flexibility” refers to the choice of the policy instrument as such, which is left to the countries themselves. National debates on which policy instruments to choose often refer to impact of such policies on the country’s competitive position with respect to its major trading partners.

The Kyoto Protocol also offers a flexibility in choosing which emissions to cut. This type of flexibility is referred to as “what flexibility.” The relevance of this type of flexibility lies in the differing marginal abatement costs of the various emissions. Models that address the first issue with respect to climate change, can be used to study such policies, but would require more detail on the emission levels of the production sectors with respect to these emission types.

Finally, there is flexibility in deciding when to start reducing emissions, so-called “when flexibility.” Studying such policies would require the use of dynamic computable general equilibrium models such as WorldScan or RICE. In particular RICE has been developed for such purposes. We refer to de Groot, who applies a predecessor RICE, DICE, to the debate on “when flexibility” [29].

The growing awareness of the potentially damaging effects of climate change due to men’s economic activities has led to the development of a quickly growing number of computable general equilibrium models to assess particular issues associated with climate change. Each model is only suited to address a subset of these issues and of the four types of flexibilities mentioned above. A complete assessment of the costs and benefits of climate change on an economy is therefore not yet possible. Future research on climate change would require the development of a computable general equilibrium model that can address all these issues and types of flexibilities. This article has provided an overview of characteristics that are essential for a cost-benefit assessment of climate change impact on the economy. These characteristics originate from different models. A computable general equilibrium model that is capable of a complete assessment of the impact of climate change on the economy should therefore at least be based on these characteristics.

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