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SIAP WORKSHOP
METHODOLOGICAL TOOLS FOR ASSESSING THE SUSTAINABILITY IMPACT OF THE EU'S ECONOMIC POLICIES, WITH APPLICATIONS TO TRADE LIBERALISATION POLICIES

7-8 November 2002 – Brussels, Belgium

Session II
Environmental Issues

Sustainable Impact Analysis: The Use of Computable General Equilibrium Models

by Christoph Boehringer

EUROPEAN COMMISSION
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Sustainable Impact Analysis:

The Use of Computable General Equilibrium Models

Christoph Böhringer
Centre for European Economic Research (ZEW), Mannheim

Paper prepared for the workshop on:

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Brussels, 7-8 November 2002

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1 INTRODUCTION

In 1987, the report of the World Commission on Environment and Development (WCED or Brundtland Commission) defined *Sustainable Development* as "development which meets the needs of the present without compromising the ability of future generations to met their own needs". In June 1992, the Rio Earth Summit concluded that "the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations.". *Sustainable Development* has meanwhile become one of the most prominent catchwords on the world political agenda. Nearly all governments and multinationals firms have committed themselves to the overall concept of *Sustainable Development*. Yet, *Sustainable Development*, which is not just about the environment, but about the economy and our society, has proven hard to define. One reason for this is that *Sustainable Development* explicitly incorporates a (normative) equity dimension, which is *„so hopelessly subjective that it cannot be analyzed scientifically"* (Young, 1994). Another reason is that the scope of the concept seems prohibitively comprehensive to make it operational in concrete practice.

Nonetheless, societal policy is challenged to come up with pragmatic approaches to *Sustainable Development* and - to this end - requires robust advice from the scientific community. Inherently, the three dimensions of *Sustainable Development*, i.e. environmental quality, economic performance (gross efficiency) and equity concerns are intertwined and subject to tradeoffs. Accomplishing one objective frequently means backpedaling on another. Since economics is the study of tradeoff, this means that there is plenty for economists to contribute in order to make the concept of *Sustainable Development* operational. One important contribution over the last years has been the assessment of external costs as a prerequisite towards "getting the prices right". Given full information on external costs, two aspects of *Sustainable Development*, namely economic performance (gross efficiency) and the environmental quality, can be merged to a comprehensive net efficiency dimension. Furthermore, while economics has little to say on equity *per se*, the sound economic quantification of distributional effects for different agents and tradeoffs between equity and efficiency objectives is a prerequisite for any rational policy debate.

The quantification of tradeoffs requires the use of numerical model techniques. There is simply no other way to think systematically and rigorously about the interaction of the many forces that interact in the economy affecting potential indicators of *Sustainable Development*. In the end, the decisions how to resolve potential tradeoffs must be taken on the basis of societal values and judgements. However, model-based analysis puts decision making on an informed basis rather than on fuzzy or contradictory hunches.

Given the broad agenda of *Sustainable Development*, the objective of this paper is to advocate computable general equilibrium (CGE) models as a methodological tool that is particularly suitable for assessing the impacts of policy interference on environmental quality, economic performance and equity. Recent developments in the field are presented that may further strengthen the role of CGE models in applied sustainable impact analysis. These developments include (i) decomposition procedures of general equilibrium effects that deliver a better understanding of key determinants for policy effects, (ii) the embedding of large-scale general equilibrium models in an optimal policy framework that considerably widens the scope of policy analysis, and (iii) systematic sensitivity analysis to test the robustness of model results with respect to uncertainties in the model's parameterization space.

The structure of the paper is as follows. Section 2 provides a brief appraisal of the CGE approach and sketches the generic structure of a multi-sector, multi-region CGE model for applied policy analysis. Section 3 describes recent methodological developments and illustrates their policy usefulness in the context of concrete policy simulations. Section 4 concludes.

2 THE GENERIC CGE APPROACH TO (SUSTAINABLE) IMPACT ANALYSIS

The general equilibrium approach is an established analytical framework for evaluating the economic implications of policy intervention on resource allocation and incomes of agents. Its main virtue is the micro-consistent representation of the direct effects as well as indirect feedbacks and spillovers induced by exogenous policy changes. The simultaneous explanation of the origin and spending of the agents' income makes it possible to address both economy-wide efficiency as well as equity impacts of policy interference.

Theoretical general equilibrium analysis provides important qualitative insights into the driving forces of adjustment reactions by economic agents to exogenous policy constraints. However, its contribution to actual policy analysis remains limited. The reason is that theoretical models are highly stylized to keep analytical tractability. As soon as certain real-world complexities are taken into account, e.g. a more detailed production structure, analytical solutions are no longer available and numerical solutions methods are required. In this context, computable general equilibrium (CGE) models have become the standard tool for applied analysis of measures in various policy domains.[1] These models incorporate lots of details and come up with concrete numbers on policy-induced economic and environmental effects. Moreover, CGE models provide an open framework for the incorporation of new economic research strings such as the new growth and trade theory or important relationships to other disciplines adopting an integrated assessment approach (see Conrad 1999, 2001 for surveys on recent developments). This flexibility makes CGE models a central methodological tool for sustainable impact analysis.

Ultimately, sustainability impact analysis requires a global and intertemporal perspective. Not only is there a need of assessing policy impacts across regions but also across generations. An intertemporal, multi-region perspective is state-of-the-art in applied CGE analysis; there are also various examples of models with overlapping generations (OLG). However, an OLG framework with multiple regions and sectors still poses considerable computational challenge and requires severe tradeoffs with the level of details that can be captured in the model.

Without loss of generality, this paper focuses on standard multi-region, multi-trade CGE models of global trade and energy use which are meanwhile employed by many international institutions, research centers, universities and consultancies. One example is the GEM-E3 model system that has been developed and applied since the early 90ies under the auspices of the European Commission.

Figure 1 provides a diagrammatic structure of a standard (one-period) model as often used for comparative-static analysis of trade and environmental policies. Primary factors of region r include labor $\overline{L}_r$, capital $\overline{K}_r$ and fossil-fuel resources $\overline{Q}_{ff,r}$. A specific resource is used in the production of crude oil, coal and gas, resulting in upward sloping supply schedules.

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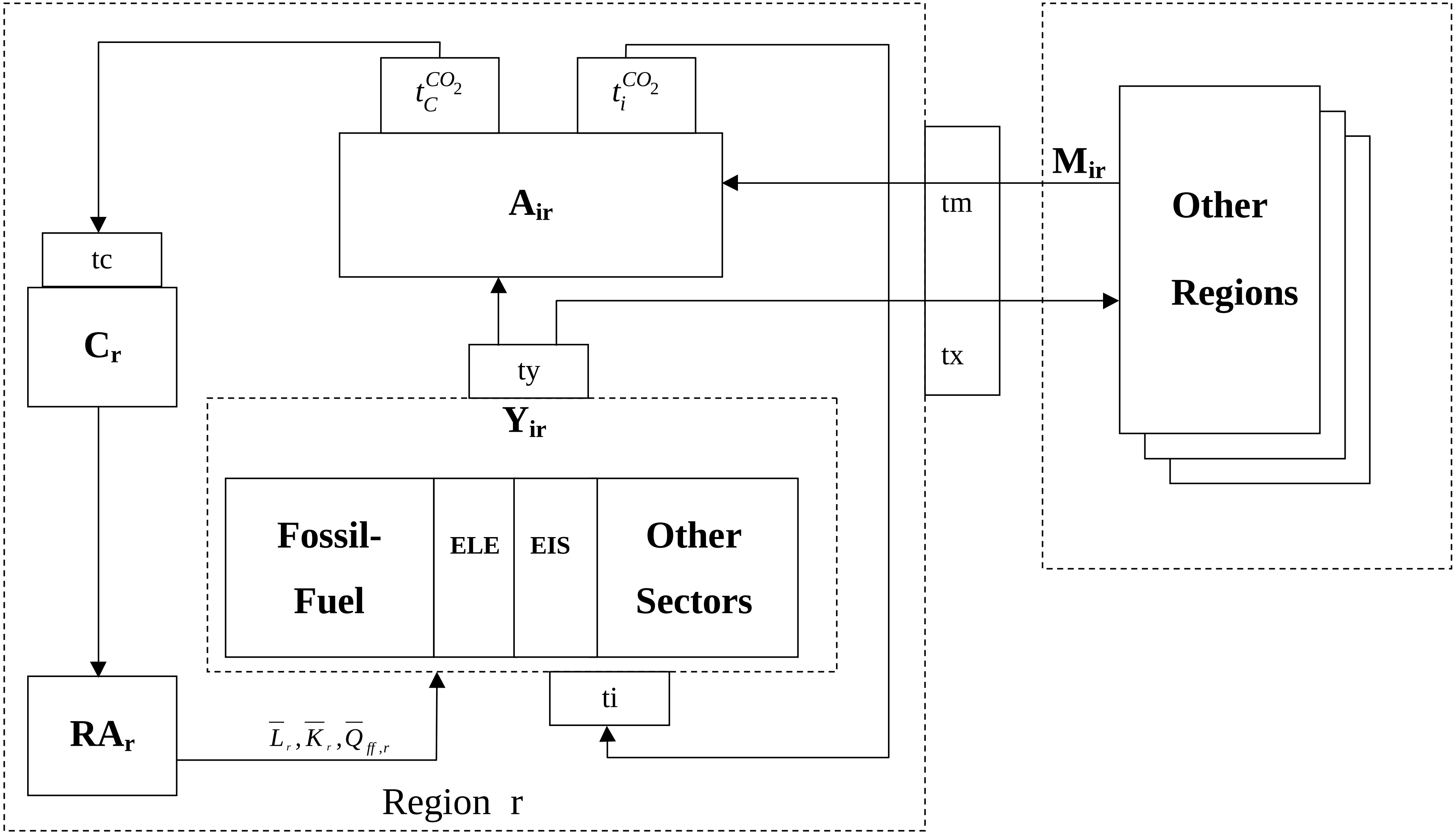
[1] See Bergman (1990), Borges (1986), Kehoe und Kehoe (1994), Klepper et al. (1995), Pereira und Shoven (1988), Shoven und Whalley (1984, 1992), Piggot und Whalley (1985, 1991), Bhattacharyya (1996), Gunning und Keyzer (1995).

Figure 1: Diagrammatic model structure



Production Y_{ir} of commodities i in region r, other than primary fossil fuels, is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs.[2] Nested constant elasticity of substitution (CES) cost functions with several levels are employed to specify the KLEM substitution possibilities in domestic production between capital (K), labor (L), energy (E) and non-energy intermediate inputs, i.e. material (M). Final demand C_r in each region is determined by a representative agent RA_r, who maximizes utility subject to a budget constraint. Total income of the representative agent consists of factor income and transfers. Final demand of the representative agent is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. The substitution patterns within the non-energy consumption bundle as well as the energy aggregate are described by nested CES functions. All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions (the so-called Armington good). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions. A governmental sector collects taxes (e.g. production taxes or subsidies *ty*, intermediate taxes *ti*, consumption taxes *tc*, tariffs *tm* and *tx*, or environmental taxes such as differentiated carbon taxes $t_i^{CO_2}$ and $t_C^{CO_2}$ on industrial and final fossil fuel use) which are used to finance the public good provision and public transfers.

The five main steps involved in constructing and using applied models are summarized in Figure 2. Initially, the policy issue must be carefully studied to decide on the appropriate model design as well as the required data. The second step involves the use of economic theory (at best, the draft of a simple analytical maquette model) in order to lay out key economic mechanisms that drive the results in the more complex numerical model. Data work, model formulation and implementation then delivers the framework for numerical policy analysis. This step also involves the set-up of alternative policy instruments and strategies that induce changes vis-à-vis the reference situation (scenario definition). In determining results of policy simulation, the choice and parameterization of functional forms are crucial. The procedure most commonly used to select parameter values is known as calibration (see Mansur and Whalley 1984). Calibration of the free parameters of functional

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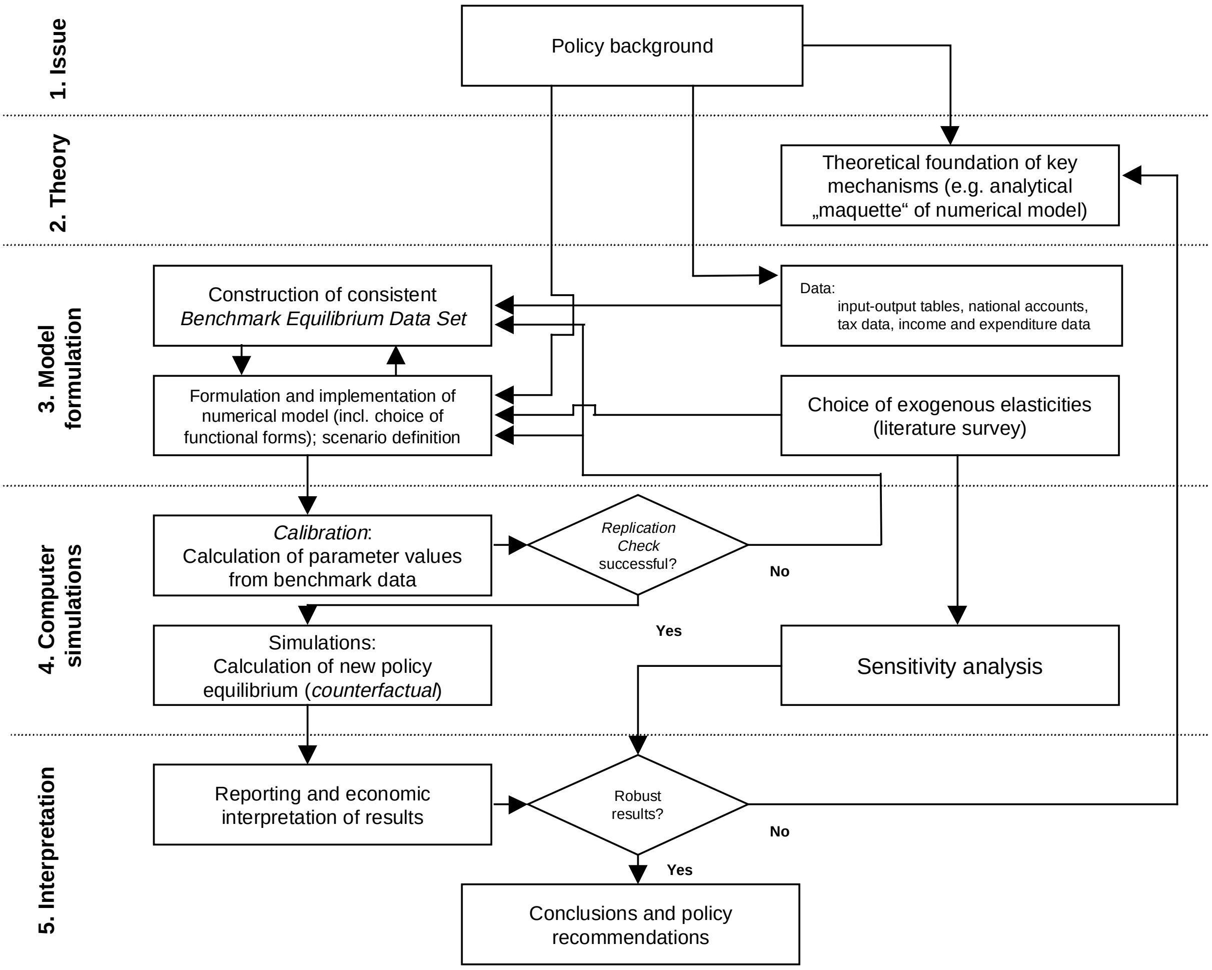
[2] In Figure 1, which is linked to the concrete policy application in section 3.2, the non fossil-fuel commodities include an energy-intensive aggregate *EIS*, electricity generation *ELE*, and *Other Sectors*.

forms requires a consistent one year's data (or a single observation represented as an average over a number of years), together with exogenous elasticities that are usually taken from literature surveys.[3]

Figure 2: Steps in CGE-based policy analysis



The calibration is a deterministic procedure and does not allow for statistical test of the model specification. The one consistency check that must necessarily hold before one can proceed with policy analysis is the replication of the initial benchmark: the calibrated model must be capable of generating the base-year (benchmark) equilibrium as a model solution without computational work. Within the policy simulations single parameters or exogenous variables are changed and a new (counterfactual) equilibrium is computed. Comparison of the counterfactual and the benchmark equilibrium then provides information on the policy-induced changes of economic variables such as employment, production, consumption,

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[3] Benchmark data is typically delivered in value terms. In order to obtain separate price and quantity observations, the common convenient procedure is to choose units for goods and factors so that they have a price of unity in the benchmark equilibrium.

relative prices, etc. Finally, the model results must be interpreted based on sound economic theory. Due to the reliance on exogenous elasticity values and a single base-year observation, comprehensive sensitivity analysis on key elasticities (and possibly alternative assumptions on economic incentives) should be performed before concrete policy recommendations are derived.

All in all, the typical CGE approach to policy analysis can be understood as theory with numbers, where a theoretical model is calibrated to observed statistics and then used for policy simulations.

Table 1 provides a selection of typical indicators in standard CGE models of global trade and energy use that could be used for quantitative tradeoff analysis along the three dimension of sustainability.

Table 1: Sustainability themes and model indicators

Sustainability themes	**Examples of possible core indicators in CGE models**
Economic aspects	
Economic development and growth	GDP (GDP per capita)
Produced assets	Net savings
...	
Social aspects	
Employment	Unemployment rate
Income	Household final consumption expenditure
....	
Environmental aspects	
Air quality	Intensity / Total of SO_x and NO_x emissions
Climate change	Intensity / Total of CO_2 emissions
....	

3 METHODOLOCIGAL EXTENSIONS

Compared to analytical models, the numerical approach accommodates the analysis of complex economic interactions and the impact assessment of structural policy changes. However, this advantage can easily turn into a disadvantage when simulation results come as black box and are not explained on the basis of rigorous economic theory. Often, the interpretation of general equilibrium effects as the total of several partial equilibrium effects is difficult, particularly if the latter can work in opposite directions. Therefore, one challenge of general equilibrium modeling is to provide decomposition methods that facilitate the isolated investigation of various partial effects contributing to the total policy impact. Section 3.1. presents two alternative decomposition techniques that can be very helpful in diagnosing the channels through which international trade transmit policy impacts between countries.

Another important extension to the standard CGE framework is the specification of optimal policy problems. This renders a *M*athematical *P*rogram with *E*quilibrium *C*onstraints (MPEC), a new class of mathematical programs introduced by Luo, Pang and Ralph (1996). The MPEC problem class permits a formal characterization of instrument design within which the objective function depends on the instrument (e.g. tax rates), i.e. policy variables that are exogenously specified in a conventional application. With respect to *sustainable* policy making, the MPEC framework allows to address central questions such as "what is the optimal tax policy to maximize economic performance given minimum constraints on the level of environmental quality or distributional concerns". Section 3.2 illustrates the use of MPECs.

Due to lack in data, CGE models are typically not econometrically estimated, but calibrated to a single benchmark equilibrium. Apart from the benchmark statistics and assumptions about the incentives of economic agents, the effects of policy interference then depend crucially on the choice of values adopted for elasticities. Extensive sensitivity analysis must be performed to test the robustness of "central case" model results before any firm policy conclusions can be drawn. In this context, section 3.3. illustrates a systematic approach to sensitivity analysis.

The techniques described in Sections 3.1 through 3.3 are generic. Applications so far have focused on the analysis of multilateral greenhouse gas abatement policies and induced trade effects. Yet, application to other fields, e.g. trade policy analysis and induced environmental effects, is straightforward.

3.1 Decomposition Techniques

Policy interventions in large open economies do not only affect the allocation of domestic resources but also change international market prices. The change in international prices implies an indirect (*secondary*) effect for *all* trading countries. This secondary terms-of-trade effect may have important policy implications. For example, international environmental agreements should account for induced changes in terms of trade when searching for "equitable" burden sharing schemes. Section 3.1.1 presents a decomposition that splits the total effect or policy changes on individual countries into a *domestic market effect* holding international prices constant and an *international market effect* as a result of changes in international prices. Splitting the total effect into these components conveys important economic information as to why a country will benefit or lose from adjustments in domestic and international markets.

In applied policy analysis, it is often relevant to link changes in endogenous variables (e.g. regions' welfare or emissions) to changes in the policy instruments (e.g. tariff rates). Such a decomposition of the total policy effect could, for example, be used to evaluate induced gains or losses from multilateral trade liberalization at the bilateral level and set up transfer or compensation systems. Section 3.2.2 describes a decomposition technique (originated by Harrison at al. 2000) to measure bilateral spillovers from policy interference.

In order to highlight the relevance of the decomposition techniques for sustainable impact analysis, sections 3.1.1 and 3.2.2 provide an application to climate change policy. The numerical simulations refer to a situation where industrialized countries apply domestic carbon taxes to meet their emission targets under the Kyoto Protocol (UNFCCC 1997).

3.1.1 Decomposing international spillovers (Böhringer and Rutherford 2002a)

The effects of policy intervention in large open economies can be broken down into a *domestic market effect*, assuming that international prices remain constant, and an *international market effect* as a result of changes in international prices. The key idea with respect to applied model analysis is that each region of a multi-region trade model (MRT) can be represented as a small open economy (SOE) in order to separate the domestic policy effect under fixed terms of trade. Policy induced changes in international prices from the multi-region model can then be imposed parametrically on the small open economy to measure the international market effect commodity by commodity.

Figure 3 illustrates the steps involved in the decomposition procedure. Computation of the domestic market effect simply requires to keep international prices at the benchmark (reference) level and then impose the domestic policy change on the specific country. Hence, for the intermediate SOE equilibrium calculation (A→B), changes on the domestic market have no effect on international prices. The spillover effect for any economic or environmental activity of a specific country is then simply the residual between the SOE equilibrium solution at benchmark terms-of-trade and the full MRT solution for the specific country (C).[4]

Figure 3: The MRT-SOE decomposition

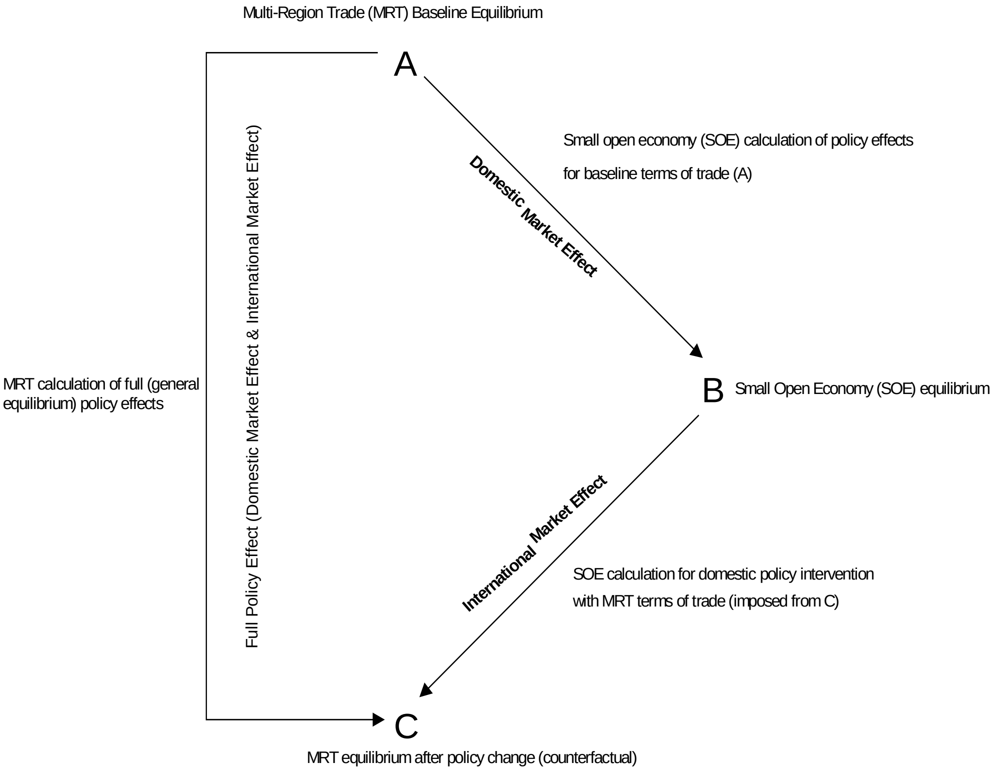

Table 2 summarizes results from the application of the decomposition method on the total welfare impacts induced by climate change policies under the Kyoto Protocol. The column *Total Policy Effect* reports aggregate consumption changes across world regions that emerge

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[4] A simple consistency check for the decomposition is as follows: Imposing the changes in international prices which are delivered by the MRT solution (A→C), one should be able to reproduce exactly the MRT solution

from carbon tax policies of signatory countries to the Kyoto Protocol for reaching their emission reduction targets in 2010.

Table 2: Welfare decomposition for carbon tax case (*NTR*)

	Domestic Market Effect (in % of BaU consumption)	Fossil Fuel Market Effect** (in % of BaU consumption)	Total Policy Effect (in % of BaU consumption)	International Spillovers* (in % of Total Policy Effect)	Carbon Tax* (in USD_{95} / ton C)	Emission Reduction (in % vs. BaU_{2010})
CAN	-0.69	-0.86	-0.88	21	230	28
CEA	0.00	0.26	0.29	100	1	-6
EUR	-0.14	-0.06	-0.06	- 116	107	14
FSU	0.00	-0.43	-1.03	100	-	-48
JPN	-0.44	-0.38	-0.30	-47	300	26
OOE	-0.13	-0.47	-0.65	81	76	16
USA	-0.36	-0.38	-0.40	9	160	27
ASI	0.00	0.26	0.14	100	-	-
BRA	0.00	0.08	0.09	100	-	-
CHN	0.00	0.26	0.20	100	-	-
IND	0.00	0.32	0.27	100	-	-
MPC	0.00	-0.77	-0.99	100	-	-
ROW	0.00	-0.05	-0.08	100	-	-

Key: CAN - Canada, CEA - Central European Associates, EUR - Europe (EU15 and EFTA), FSU - Former Soviet Union (Russian Federation and Ukraine), JPN - Japan, OOE - Other OECD (Australia and New Zealand), USA - United States, ASI - Other Asia (except for China and India), BRA - Brazil, CHN - China (incl. Hong Kong and Taiwan), IND - India, MPC - Mexico and OPEC, ROW - Rest of World

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

[**] Welfare change accounting for domestic market effect and international price changes for crude oil and coal

Tax-induced reallocation of resources due to emission constraints (e.g. fuel shifting or energy savings) causes substantial adjustment costs for OECD countries. Furthermore, there are considerable international spillover effects from abating industrialized countries to non-abating countries: Adjustments on international markets induce welfare losses for FSU as well as MPC and, to a much smaller extent, for ROW. All other non-abating countries benefit to varying degrees from the changes in international prices associated with emission abatement in OECD countries.

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from the SOE perspective (B→C).

Application of the decomposition method allows to gain insights into the different sources of welfare changes across regions. Table 2 lays out how the economic impact of carbon taxes turns from the domestic market effect into the total policy effect as changes in international prices are successively imposed upon the SOE sub-models. The column *International Spillovers* indicates the magnitude of international spillovers measured in percent of the total policy effect. Obviously, the international spillovers is identical to the total policy effect for those countries which do not undertake domestic abatement, i.e. countries whose domestic market effect is zero. As to abating countries, the decomposition provides information on the sign and relative magnitude of the primary domestic and the secondary international impacts. International spillovers are negative for USA, CAN and OOE, whereas CEA, EUR, and JPN benefit from the adjustments on international markets.

Regarding international spillovers, most important are the adjustments on international coal and crude oil markets (see column *Fossil Fuel Market Effect*). The cutback in demands for fossil fuels from abating OECD countries depresses the international prices for oil and coal. As a consequence, countries which are net importers of coal and crude oil gain, whereas net exporting countries lose. For CAN, MPC, and ROW, which are net exporters of both coal and crude oil, the aggregate welfare effect is unambiguously negative. Likewise, net importers EUR, JPN, CHN, IND, BRA and ASI experience welfare gains. For countries which are net importer of one fossil fuel *and* net exporter of the other, the aggregate effect depends on export and import quantities as well as the relative changes in international coal and crude oil prices.

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

To sum up: Application of the decomposition method to emission regulation under the Kyoto Protocol reveals that among signatory countries, Australia, Canada, New Zealand and USA bear a secondary burden through changes in international terms of trade, whereas Europe and Japan experience secondary benefits. Most developing countries gain a comparative advantage due to abatement in Annex B regions, but fossil fuel exporters such as Mexico and OPEC are seriously hurt. A major determinant for the differences in sign and magnitude of spillovers is the trade position of countries on international coal and crude oil markets: Depressed international prices for fossil fuels, that are due to the cutback in global fossil energy demand, provide gains for fossil fuel importers and losses for fossil fuel exporters.

3.1.2 Decomposing bilateral spillovers (Böhringer and Rutherford 2002b)

Harrison, Horridge, and Pearson (HHP) propose a generic linear decomposition methodology for calculating the contributions of multiple exogenous policy instruments to the resulting changes in individual endogenous variables (Harrison et al. 200). The HHP method can be explained along a simplified example in which an *endogenous* variable Z is expressed as an explicit function of a vector of *exogenous* variables $\overrightarrow{X}$ (the policy instruments):

$$Z = F(\overrightarrow{X}) = F(x_1, x_2, ..., x_n)\ .$$

A change in the exogenous policy instruments $\overrightarrow{X}$ induces an endogenous change ΔZ in Z. For policy analysis, it is often useful to attribute changes in the endogenous variable to changes in the policy instruments. One way of decomposing the total change ΔZ in the endogenous variable with respect to the individual contributions from exogenous variables would be a sequential approximation of the impacts of *one* exogenous variable while keeping *all others* constant. Assuming that *F* is differentiable, the contribution of a change in the *i*-th exogenous variable to ΔZ (as x_i moves from the initial value x_i^0 to the new value x_i^1) can then be computed as the line integral:

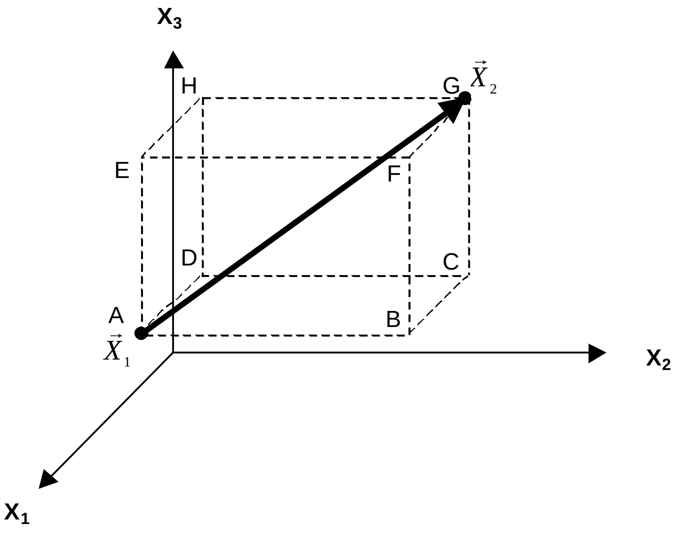
$$\Delta Z\big|_{x_i} = \int_{x_i^0}^{x_i^1} \frac{\partial F}{\partial x_i} dx_i\ .$$

For the numerical computation, the total change in the exogenous variable Δx_i is divided into sufficiently small steps to approximate the line integral through linearization.

When F is nonlinear, the total change from shocks in exogenous variables can not be decomposed in additive line-integrals for each exogenous variable starting from the initial value Z^0. The impact of a change in an exogenous variable must be calculated, taking into account the contributions of *previous* changes in other exogenous variables. This implies that the decomposition is potentially sensitive to the sequential ordering of changes in the exogenous policy variables. As there are *n!* ways of sequential ordering of *n* exogenous variables, one quickly ends up with a large number of (possibly) different decompositions for relatively small-scale policy experiments. For many policy packages (including multilateral emission abatement contracts, such as the Kyoto Protocol) no one sequential decomposition might be obviously more plausible than any other. HHP therefore suggest an order-independent "natural " way of calculating contributions. On the "natural" path, the exogenous variables move *together at the same rate* towards their final value along a straight line between their starting values $\overrightarrow{X}^0$ and the final values $\overrightarrow{X}^1$. The straight line between these points is obtained by changing the elements of $\overrightarrow{X}$ as a differentiable function H of some parameter t holding the rate of change in the exogenous variables constant along the path (where $\overrightarrow{X}^0 = H(t = t^0), \overrightarrow{X}^1 = H(t = t^1)$).

Figure 4 illustrates the difference between the sequential method of decomposition and the HHP approach. In contrast to moving along the *edges* of the policy cube, the HPP method follows a straight line between the pre- and post-simulation values.

Figure 4: Sequential ordering versus "natural "path



For n exogenous variables, the total change in the endogenous variable is equal to:

$$\Delta Z = \sum_{i=1}^{n} \int_{t=t^0}^{t=t^1} \frac{\partial F}{\partial x_i} \frac{dx_i}{dt} dt$$

This concept is easily generalized to the case where the relationship between exogenous and endogenous variables is implicit, which is typically the case for computable general equilibrium models used for the economic analysis. As HHP point out, it is possible to calculate numerical values for the gradients $\frac{\partial F}{\partial x_i} \frac{dx_i}{dt}$ at all points of the "natural" path by solving a system of linear equations. The individual contributions of changes in policy instruments x_i can then be approximated through linearization of the respective line integral which involves solving a system of linear equations R times, where R renders a sufficiently small step-size $\Delta t / R$ (with $\Delta t = t^1 - t^0$).

Application of the HHP decomposition to climate change policies provides concrete estimates for bilateral spillovers that might be useful for the delicate policy issue of who should pay for adverse international spillovers to developing countries.[5] The HHP procedure avoids arbitrariness in the calculation of spillovers as compared to any sequential ordering of abatement policies in industrialized countries.

The results, presented in Table 3, show the percentage of the welfare cost for each region (rows) attributable to carbon taxes in each of the industrialized regions (columns). These numbers are obtained by evaluating a line integral where the carbon *taxes* across abating regions are change at equal rates starting from zero and ending with the final carbon taxes as reported in Table 2.

Matrix elements with negative signs indicate that the effect of the abatement policy by the column region is opposite to the sign of the total welfare change for the row region. For example, the value of – 30 at the intersection of *row* ASI with *column* JPN means that abatement actions in JPN induce a welfare *loss* in ASI (since overall the welfare impacts for ASI are positive).

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[5] The United Nations Framework Convention on Climate Change (UNFCC 1992) guarantees compensation from industrialized countries to the developing world for adverse spillovers from emission abatement in the industrialized world (Articles 4.8 and 4.9).

Table 3: Decomposition of welfare impacts

	Welfare impact		Percentage of the welfare cost for each region (rows) attributable to carbon taxes in each of the Annex B regions (columns)				
	in % vs. BaU	in bn USD$_{95}$	CAN	EUR	JPN	OOE	USA
CAN	-0.88	-0.62	87	6	4		2
CEA	0.29	0.10	11	24	18	1	47
EUR	-0.06	-0.69	-15	250	-25	-4	-105
FSU	-1.03	-0.51	3	40	4		52
JPN	-0.30	-1.65	-6	-12	148	-1	-29
OOE	-0.65	-0.33	3	13	12	33	39
USA	-0.40	-3.60	2	-4	-5	-1	107
ASI	0.14	0.24	12	19	-30	2	96
BRA	0.09	0.14	11	14	20	2	53
CHN	0.20	0.43	7	18	15	2	59
IND	0.27	0.16	7	17	15	2	59
MPC	-0.99	-1.71	9	19	20	1	51
ROW	-0.08	-0.19	15	31	51	6	-3
Total	-0.22	-8.23					

Matrix elements with positive signs denote that the impact of the abatement policy in the column region on the row region has the same sign as the total welfare impact of the row region. For example, a positive *row* entry for MPC, which in total is negatively affected by abatement in industrialized countries, reveals that action of the respective column region produces negative welfare spillovers. The diagonal elements for abating regions reveal the percentage of their aggregate welfare changes due to their own policy. The *own-policy* effect dominates the aggregate of the *foreign-policy* effects, except for OOE and, in particular, for CEA, which impose rather small domestic carbon taxes.

Reading down the *column* USA in Table 3, we find that abatement actions by the USA produce by far the largest spillovers to other countries. The main source for these spillovers are larger adjustments on the international fossil fuel markets due to the substantial cutbacks in US fossil energy demands. Emission constraints in the USA account for the bigger part of the decline in fossil fuel producer prices following multilateral abatement under the Kyoto Protocol. This produces positive bilateral spillovers to fuel importers, such as EUR, JPN and developing regions ASI, BRA, CHN, as well as IND. Fuel exporters, such as CAN, MPC or ROW, are negatively affected. At the other end of the impact spectrum, we find OOE and

CEA, whose spillovers to other regions are rather negligible due to their moderate tax rates and small shares in overall trade volumes. Reading Table 3 by rows, we obtain information on how a country is affected by the carbon taxes of abating industrialized countries.

The percentage changes in welfare from individual policy action as reported in Table 4 can be translated into monetary units. Table 4 presents the matrix of compensating (net) transfer payments that must be assigned on a bilateral basis in order to provide compensation for spillovers from abatement policies in individual industrialized countries. A negative entry indicates compensation claims of the *row* region towards the *column* region.

Table 4: Compensating transfers from region (rows) to region (column) in billion dollars annually between 2008 and 2012

	CAN	CEA	EUR	FSU	JPN	OOE	USA
CEA	0.01						
EUR	0.14	-0.02					
FSU	-0.02		-0.2				
JPN	0.12	-0.02	0.03	0.02			
OOE	-0.01		-0.07		-0.06		
USA	-0.06	-0.05	-0.58	0.27	-0.3	0.17	
ASI	0.03		0.05		-0.07		0.23
BRA	0.02		0.02		0.03		0.07
CHN	0.03		0.08		0.06	0.01	0.25
IND	0.01		0.03		0.02		0.1
MPC	-0.15		-0.32		-0.34	-0.02	-0.87
ROW	-0.03		-0.06		-0.1	-0.01	0.01

Tables 3 and 4 reveal fundamental problems underlying the issue of compensation to developing countries for induced economic costs. A developing region may benefit from abatement in one industrialized country, but suffer from abatement in other industrialized regions. This raises the question of whether developing countries that are compensated for adverse spillovers on the one hand should pay for positive spillovers on the other hand. To put it differently, industrialized countries that compensate for adverse spillovers to some developing countries may well claim transfers from those developing countries which benefit from their abatement policy.

3.2 The MPEC Framework

A relatively new research area in applied general equilibrium analysis is based on *M*athematical *P*rograms with *E*quilibrium *C*onstraints (MPEC), a new class of mathematical programs introduced by Luo, Pang and Ralph (1996). The MPEC problem class permits a formal characterization of optimal policies within which the objective function depends on policy variables (e.g. tax rates) that would be exogenously specified in a conventional CGE application.

In formal terms, the optimal policy problems in CGE models can be expressed as a specific case of the general MPEC formulation:

$$\max_{t} \; f(z;t)$$

s.t. z solves the equilibrium constraints *F(z;t)*

where:

$t \in \mathbb{R}^m$	is a vector of policy (instrument) variables which are the choice variables for the problem,
$z \in \mathbb{R}^n$	is a vector of endogenous variables that is determined by the equilibrium problem, i.e. $z = \begin{pmatrix} p \\ y \end{pmatrix}$, where *p* are prices and *y* are activity levels,
F(z; t)	is a system of equations which represents market equilibrium conditions, and
$f : \mathbb{R}^{n+m} \rightarrow \mathbb{R}^1$	is the objective function.

Böhringer and Rutherford (2002c) provide a large-scale MPEC application to design optimal carbon tax programs in a static multi-region, multi-sector general equilibrium model of global trade and energy use. In their case, the constraints *F(z; t)* describe the equilibrium conditions of a standard multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use. *F(z; t)* includes an emission reduction constraint for an open economy that can be achieved through the use of (endogenous) emission taxes. The taxes correspond to the set of choice variables *t* in the optimal taxation problem and can be differentiated across different segments of the economy to maximize an objective such as overall real consumption. Böhringer and Rutherford (2002c) use the optimal tax framework to assess the relative importance of four alternative arguments that might justify the common policy practice of environmental tax differentiation: initial tax distortions, distributional concerns, leakage motives or international market power. Simulation results for the European and U.S. economies suggest conclude that there is little economic rationale for the common policy practice to discriminate strongly in favor of heavy industries. Among the four motives for tax differentiation examined, only very specific concerns about job layoffs give reasons for tax exemptions to energy-intensive industries. Concerns about global environmental effectiveness provide some justification for tax discrimination in favor of energy- and export-intensive industries although leakage must be very high to make the case for substantial tax reductions. Tax interaction with initial fiscal energy taxes, broader-ranged concerns about factor incomes, as well as strategic international tax burden shifting can hardly rationalize the current practice in OECD countries to have only very low environmental taxes on energy-intensive industries or even exempt them.

3.3 Systematic Sensitivity Analysis

A wide-spread criticism to CGE analysis is the deterministic calibration approach to specify parameters of functional forms. Clearly, a stochastic estimation of parameters would be preferable. However, a (complete) econometric estimation of large-scale general equilibrium systems is typically doomed to failure due to severe data problems. The simultaneous estimation of all parameters would either require unrealistically large numbers of observations or overly severe identifying restrictions. The pragmatic way is to stick with the calibration approach and to check the sensitivity of central model results with respect to uncertainties in the elasticity space.

One approach to systematic sensitivity analysis is to conduct Monte Carlo simulations where values for key elasticties (e.g. trade elasticities, energy demand elasticities and fossil fuel supply elasticities) are drawn from uniform probability distributions around the model central values. Table 5 provides an illustrative statistical summary of results for CGE policy simulations on the economic effects of the Kyoto Protocol (see Böhringer and Vogt 2002). The summary includes the core (central case) values together with the mean and the median as well as the 5 % quantile and 95 % quantile. Such statistics provide useful insights into the robustness of model results.

Table 5: Results of Monte Carlo simulations on Kyoto Protocol (Böhringer and Vogt 2002)

Scenario:	*Implementation of Kyoto by domestic carbon taxes of industrialized countries*				
	core value	mean	median	5% quantile	95% quantile
Consumption change in % vs. BaU					
OOE	-1.18	-1.16	-1.14	-1.38	-1.01
CAN	-1.48	-1.43	-1.42	-1.59	-1.31
EUR	-0.17	-0.19	-0.20	-0.23	-0.14
JPN	-0.26	-0.31	-0.31	-0.38	-0.21
CEA	0.49	0.50	0.50	0.29	0.73
FSU	-0.93	-0.88	-0.87	-1.04	-0.74
USA	-0.51	-0.56	-0.53	-0.78	-0.42
ROW	-0.35	-0.31	-0.30	-0.42	-0.24
TOTAL	-0.24	-0.25	-0.25	-0.31	-0.21
Marginal abatement costs in USD97 per ton of carbon					
OOE	126	135	124	92	207
CAN	145	154	145	112	222
EUR	111	114	110	88	149
JPN	183	191	181	139	270
CEA	0	0	0	0	0
FSU	0	0	0	0	0
USA	156	170	156	114	271
Consumption change in USD97 per capita					
OOE	-114	-113	-110	-134	-99
CAN	-162	-155	-153	-174	-141
EUR	-23	-25	-26	-31	-18
JPN	-53	-61	-61	-76	-43
CEA	8	8	8	5	12
FSU	-12	-11	-11	-13	-9
USA	-92	-102	-96	-142	-76
Emission reduction in % vs. BaU					
TOTAL	9.60	9.51	9.50	9.00	10.00

4 CONCLUSIONS

Computable general equilibrium (CGE) models provide a flexible tool for sustainable impact assessment. These models can incorporate lots of sustainability (meta-)indicators in a single consistent framework and allow for a systematic quantitative tradeoff analysis along the three dimension of sustainability. Decomposition methods can be employed to better understand the complex adjustment mechanisms triggered by exogenous policy changes. The decomposition of general equilibrium results may also deliver valuable information for the proper design of policies. Furthermore, recent computational developments permit the formulation of optimal policy problems within large-scale CGE models. This class of models then can help to determine the set and intensity of *optimal* policy instruments for sustainable development..

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