View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Research Papers in Economics

ECONSTOR

WWW.ECONSTOR.EU

Der Open-Access-Publikationsserver der ZBW – Leibniz-Informationszentrum Wirtschaft
The Open Access Publication Server of the ZBW – Leibniz Information Centre for Economics

Böhringer, Christoph; Löschel, Andreas; Rutherford, Thomas F.

Working Paper

Efficiency Gains from "What"-Flexibility in Climate Policy: An Integrated CGE Assessment

ZEW Discussion Papers, No. 04-48

Provided in cooperation with:
Zentrum für Europäische Wirtschaftsforschung (ZEW)

Suggested citation: Böhringer, Christoph; Löschel, Andreas; Rutherford, Thomas F. (2004) : Efficiency Gains from "What"-Flexibility in Climate Policy: An Integrated CGE Assessment, ZEW Discussion Papers, No. 04-48, http://hdl.handle.net/10419/24074

Nutzungsbedingungen:
Die ZBW räumt Ihnen als Nutzerin/Nutzer das unentgeltliche, räumlich unbeschränkte und zeitlich auf die Dauer des Schutzrechts beschränkte einfache Recht ein, das ausgewählte Werk im Rahmen der unter
→ http://www.econstor.eu/dspace/Nutzungsbedingungen
nachzulesenden vollständigen Nutzungsbedingungen zu vervielfältigen, mit denen die Nutzerin/der Nutzer sich durch die erste Nutzung einverstanden erklärt.

Terms of use:
The ZBW grants you, the user, the non-exclusive right to use the selected work free of charge, territorially unrestricted and within the time limit of the term of the property rights according to the terms specified at
→ http://www.econstor.eu/dspace/Nutzungsbedingungen
By the first use of the selected work the user agrees and declares to comply with these terms of use.

ZBW Leibniz-Informationszentrum Wirtschaft
Leibniz Information Centre for Economics

Mitglied der Leibniz-Gemeinschaft

Discussion Paper No. 04-48

Efficiency Gains from "What"-Flexibility in Climate Policy

An Integrated CGE Assessment

Christoph Böhringer, Andreas Löschel, and
Thomas F. Rutherford

ZEW
Zentrum für Europäische
Wirtschaftsforschung GmbH
Centre for European
Economic Research

Discussion Paper No. 04-48

Efficiency Gains from "What"-Flexibility in Climate Policy

An Integrated CGE Assessment

Christoph Böhringer, Andreas Löschel, and
Thomas F. Rutherford

Nontechnical Summary

The United Nations Framework Convention on Climate Change's stated goal is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Article 2). Given some stabilization or likewise temperature targets, rational climate policy should minimize the net economic costs of limiting temperature change. Cost-effectiveness suggests that the marginal costs of emission control should be equalized across all sources in space and time. This comes down to comprehensive "where", "when", and "what"-flexibility. With the first, reductions should take place *where* it is cheapest, regardless of the geographical location. With the second, reductions should take place *when* the cost-benefit calculus yields a positive value. With the third, decisions can be taken on *what* greenhouse gas should be abated under cost-effectiveness considerations.

While the potentials for efficiency gains from "where"-flexibility have been investigated in broader detail, quantitative analysis of "when"-flexibility and "what"-flexibility is rather limited. The reason is that an appropriate treatment of "when"- and "what"-flexibility requires a sophisticated long-term analytic framework that combines some form of climate model with a model of global economic activity.

The primary objective of this paper is to lay out such an integrated framework for evaluating efficient multi-gas emission control strategies. We present a multi-sector, multi-region computable general equilibrium model (PACE) that features a reduced from representation of the key links between anthropogenic emissions of different greenhouse gases and climate change (radiative forcing and temperature). Based on numerical simulation with this integrated assessment model we investigate the importance of "what"-flexibility on top of "where"- and "when"-flexibility for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. We find that "what"-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only dependent on absolute temperature change but also on the rate of temperature change.

Efficiency Gains from "What"-Flexibility in Climate Policy
An Integrated CGE Assessment

Christoph Böhringer
Centre for European Economic Research (ZEW), Mannheim
Faculty of Economics and Social Studies, University of Heidelberg,

Andreas Löschel
Centre for European Economic Research (ZEW), Mannheim

Thomas F. Rutherford
Department of Economics, University of Colorado

Abstract

We investigate the importance of "what"-flexibility on top of "where"- and "when"-flexibility for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. We find that "what"-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only dependent on absolute temperature change but also on the rate of temperature change.

JEL classification: D58; Q43

Keywords: Climate policy; Integrated Assessment; What-flexibility

1. Introduction

Flexibility is a central element in market-based economies in order to foster the efficient use of scarce resources. In the context of climate policy, efficiency translates into questions of how much and what anthropogenic greenhouse gas (GHG) emissions should be abated, when, and where, i.e. by whom. Given complete information, comprehensive cost-benefit analysis could deliver precise answers to these questions. However, neither costs nor benefits of GHG emission abatement are easy to quantify. In particular, there are large uncertainties in external cost estimates for climate change. The chain of causality – from GHG emissions to ambient concentrations of GHGs in the atmosphere, from temperature increase to physical effects such as climatic and sea level changes – is very complex. Moreover, economists do not even agree on the methodology to be used for valuing such potential climate change impacts as the extinction of a species. The large uncertainties in predicting global climate change, as well as quantifying and monetizing the associated biophysical impacts explain much of the controversy on the desirable long-term level of GHG concentrations in the atmosphere and the scope and timing of emission mitigation measures.

Presuming that uncertain future outcomes of climate change could be extreme and irreversible, risk aversion may justify the adoption of a precautionary cost-effectiveness approach rather than hinging on traditional cost-benefit analysis (Gollier et al. 2000). In this vein, the United Nations Framework Convention on Climate Change (UNFCCC) aims at establishing an ample margin of safety based on recommendations from natural science on "tolerable" emission levels. The UNFCCC's stated goal is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC 1992, Article 2). In its Third Assessment Report the Intergovernmental Panel on Climate Change (IPCC), which serves as the scientific advisory board to the UNFCCC, laid out several long-term stabilization scenarios for greenhouse gas emissions with an associated range of expected increases in the global mean temperature (IPCC 2001). Given some stabilization or likewise temperature targets, rational climate policy should minimize the net economic costs of limiting temperature change. Cost-effectiveness suggests that the marginal costs of emission control should be equalized across all sources in space and time.[1] This comes down to comprehensive "where", "when", and "what"-flexibility. With the first, reductions should take place *where* it is cheapest to do so,

---

[1] Note that - in contrast to cost-benefit analysis – it is no longer assured that marginal costs are equal to the marginal benefits of emission reduction.

regardless of the geographical location. With the second, reductions should take place *when* the cost-benefit calculus yields a positive value. With the third, decisions can be taken on *what* greenhouse gas should be abated under cost-effectiveness considerations.

While the potentials for efficiency gains from "where"-flexibility have been investigated in broader detail (see e.g. Weyant 1999), the implications of "when"-flexibility have been analyzed less intensively, and there are only relatively few studies that have addressed aspects of "what"-flexibility. There are good reasons for the shortage of studies on "when"- and "what"-flexibility. First, the quality of data for sources and abatement options of GHGs other than CO_2 is poor. Second, an appropriate analysis of "when"- and "what"-flexibility demands for integrated assessment of economic and climatic relationships in a dynamic framework that poses considerable challenges to modeling. Third, the long-term nature of climate change implies substantial uncertainties in economic analysis as it requires tenuous assumptions on the business-as-usual development that will be a key driver for adjustment costs to some climate policy objective.

Against this background, the primary objective of this paper is to ascertain the relative importance of a multi-gas emission control strategy (in our case: CO_2 *and* CH_4) vis-à-vis a CO_2-only abatement strategy. In other words: We want to sort out how much can be gained if we put "what"-flexibility on top of "where"- and "when"-flexibility. The explanatory power of such a comparison depends crucially on the proper design of the overall analytical framework. Therefore, we place special emphasis on the description of the baseline calibration and the integration of climate relationships into PACE, a dynamic multi-sector, multi-region computable general equilibrium (CGE) model of global trade and energy use.

Based on numerical simulation with this integrated assessment model we find that "what"-flexibility substantially reduces the compliance costs under alternative emission control schemes. When comparing policies that simply involve long-term temperature targets against more stringent strategies that include additional constraints on the rate of temperature increase, it turns out that the latter involve huge additional costs. These costs may be interpreted as additional insurance payments if damages should not only dependent on absolute temperature change but also the rate of temperature change. Our calculations also confirm the shortcomings of the global warming potential (GWP) approach to represent the contribution of different greenhouse gases to global temperature change because the relative contribution may vary substantially over time.

The remainder of this paper is organized as follows. Section 2 lays out the generic general equilibrium framework that serves as a starting point for subsequent extension to accommodate integrated assessment of multi-gas abatement strategies. Section 3 describes the baseline calibration of our model to long-term projections on economic growth and energy use. Section 4 elaborates the inclusion of non-CO2 greenhouse gases (in our case: CH_4). Section 5 provides a summary of the reduced-form climate sub-module and its linkage to the energy-economy model. Section 6 outlines the policy scenarios and interprets the simulation results. Section 7 concludes.

2. Generic Model Structure

Computable general equilibrium (CGE) models have become the standard tool for the analysis of the economy-wide impacts of greenhouse gas abatement policies on resource allocation and the associated implications for incomes of economic agents (see e.g. Bergmann 1990, Grubb et al. 1993, Weyant 1999). The main reason for this is that the general equilibrium framework represents price-dependent market interactions as well as the origination and spending of income for various economic agents based on rigorous microeconomic theory.

In this section, we lay out the generic structure of a multi-sector, multi-region CGE framework of global trade and energy use. A multi-region framework is indispensable for the analysis of global GHG emission constraints. In a world that is increasingly integrated through trade, policy interference in open economies not only cause adjustment of domestic production and consumption patterns but also influence international prices via changes in exports and imports. The changes in international prices, i.e. the terms of trade, imply secondary effects, which can significantly alter the impacts of the primary domestic policy (Böhringer and Rutherford 2002). In addition to the consistent representation of trade links, a detailed tracking of energy flows is a pre-requisite for the assessment of climate policies. Combustion of fossil fuels is a driving force of global warming through the release of the man greenhouse gas CO_2 (CH_4 also originates to a significant share from fossil fuel production and consumption). Beyond the comprehensive spatial coverage, climate policy analysis requires an explicit dynamic framework since policy interference applies over longer time periods as climate change is an inherently dynamic problem and happens on larger time scales. On the consumption side, dynamics involve the representation of the savings behavior of households. On the production side, dynamics involve the description of investment decisions of firms. To build dynamic features into the modeling of the economic behavior of households and firms one has to make an assumption on the degree of foresight of the economic agents. Assuming that the agents in the model know as much concerning the future as the modeler, implies a model with "consistent expectations" or "perfect foresight" where all agents consistently anticipate all current and future prices ("clairvoyance"). Such a framework reveals plausible effects of policy changes on intertemporal consumption and investment (savings) decisions and allows for the measurement of transitional effects that can be significant relative to long-term impacts.

Below, we first provide a short non-technical summary on the static intra-period sub-module and then describe the dynamics of the overall model. Finally, we point out the advantage of implementing the model in a mixed complementarity format rather than adopting a nonlinear programming (optimization) approach.

2.1. The Static Sub-Module

Figure 1 lays out the diagrammatic structure of the single-period static sub-module that underlies our dynamic multi-sector multi-region CGE model of global trade and energy use PACE. Primary factors of a region *r* include labor, capital and resources of fossil fuels *ff* (crude oil, coal, and gas). The specific resource used in the production of crude oil, coal and gas results in upward sloping supply schedules. 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. Nested constant elasticity of substitution (CES) cost functions with several levels are employed to specify the KLEM substitution possibilities in domestic production sectors between capital (K), labor (L), energy (E) and non-energy intermediate inputs, i.e. material (M).

Final demand C_{ir} of the representative agent RA_r in each region 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. CO_2 emissions are associated with fossil fuel consumption in production, investment, and final demand.

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 (Armington, 1969). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions.

Endowments of labor and the specific resources are fixed exogenously. Capital supplies are price-responsive (see section 2.2.). Within any time period, we assume competitive factor and commodity markets such that prices adjust to clear these markets.

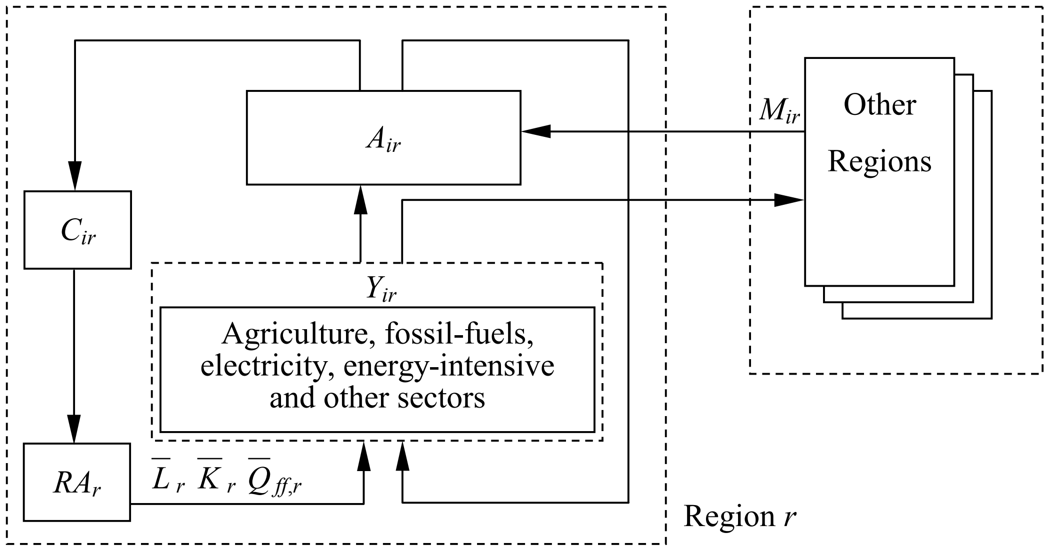

Figure 1: Structure of the intra-period sub-module

2.2. Dynamics

The notion of consistent expectations is coupled with the simplifying assumption of an infinitely-lived representative agent who makes explicit choices at the margin between current and function consumption. The representative agent maximizes welfare subject to an intertemporal budget constraint. In equilibrium the present value of consumption equals the present value of income over the infinite horizon. Within a given period, however, a region may run a current account surplus or deficit, depending on the difference between national income and expenditure.[2]

Figure 2 illustrates the basic dynamics of the model. The representative agent for each region maximizes his discounted utility over the model's time horizon. The primary factors, capital, labor, and energy are combined to produce output in period *t*. In addition, energy is delivered directly to final consumption. Output is divided between consumption and investment, and investment augments the (depreciated) capital stock in the next period. Capital, labor, and the energy resource earn incomes, which are either spent on consumption or retained for savings, i.e. investment.

---

[2] Closure of financial flows within the model implies that the deficit is equal to the difference between the value of commodity imports and commodity exports.

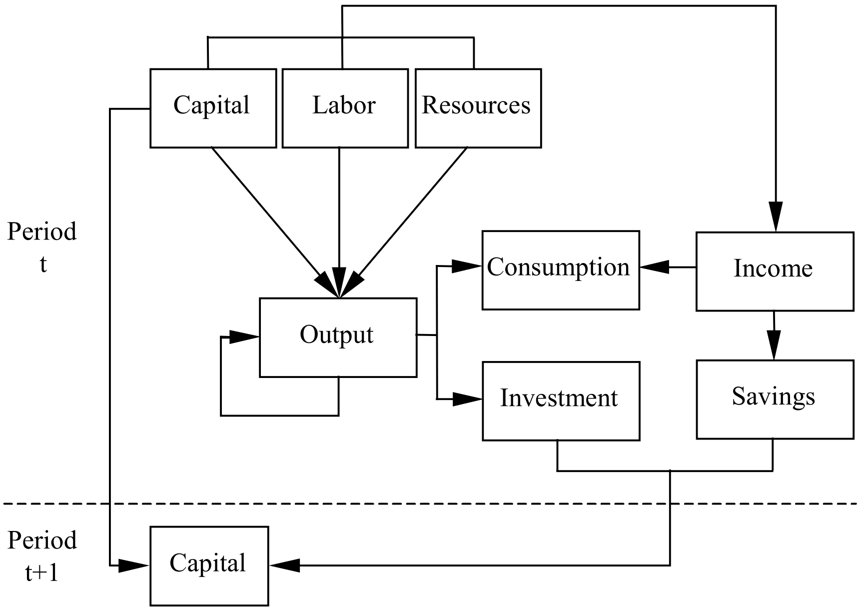

Figure 2: Dynamic model settings

Investment is driven by consistent expectations where the return on investment (with quadratic adjustment costs) is balanced against the cost of capital. In equilibrium, investments are placed in the region (sectors) where they will receive the highest return. International capital flows are thus endogenous, and the demand and supply of savings jointly determine the international interest rate. The baseline equilibrium growth path is calibrated to a common marginal product of capital in all regions. Capital stocks evolve through constant geometric depreciation and new investment. Following Uzawa (1969), we assume that capital installation costs depend on the rate of gross investment (relative to the existing capital stock). Given the level of investment, the cost of new capital decreases when the capital stock increases and vice versa. A quadratic installation cost function relates net to gross investment. For large adjustment costs, rapid changes in the regional capital stock are costly and the model exhibits a slower speed of adjustment of capital stocks to changes in the rate of return.[3]

Dynamic general equilibrium models exhibit a turnpike property, and one can exploit this when an infinite horizon equilibrium must be approximated with a finite model. To assure invariance of model results with respect to the time horizon, a set of appropriate terminal conditions must be specified. We adopt here the strategy proposed by Lau et al. (2002) where (i) terminal capital stocks are chosen to be consistent with smooth growth in investment in the final

---

[3] Note that when there are no adjustment costs, the model reduces to the standard Ramsey model.

periods of the model and (ii) terminal assets are determined in consistency with budget balance and steady-state growth for the post-terminal horizon.

2.3. MCP Implementation

Algebraically, our model is implemented as a mixed complementarity problem (MCP). The MCP formulation provides a general format for economic equilibrium problems that may not be easily studied in an optimization context. Only if the complementarity problem is “integrable” (see Takayma and Judge 1971), the solution corresponds to the first-order conditions for a (primal or dual) programming problem. Given integrability, the nonlinear optimization problem can be interpreted as a market equilibrium problem where prices and quantities are defined using duality theory. In this case, a system of (weak) inequalities and complementary slackness conditions replace the minimization operator (see e.g. Rutherford 1995).[4] However, taxes, income effects, spillovers and other externalities, interfere with the skew symmetry property which characterizes first order conditions for nonlinear programs. In contrast to various models for long-term policy assessment that adopt an explicit optimization approach (see e.g. Manne and Richels 2001), our modeling framework is directly suited to investigate policy interference in (real-world) second-best settings. Compared to equilibrium conditions cast as system of equations the MCP framework allows for a straightforward representation of restrictions on prices or quantities that may become binding in equilibrium or not. Numerically, the model is implemented in MPSGE (Rutherford 1999) as a subsystem of GAMS (Brooke et al. 1986) using PATH (Dirkse and Ferris 1995) for solving the MCP problem.

3. Calibration

In quantitative policy analysis, the effects of policy interference are measured with respect to a reference situation - usually termed business-as-usual (BaU) - where no policy changes apply. When we want to simulate the potential effects of some policy measure, information on the future BaU development is required. Apparently, the BaU projections are a crucial determinant for the overall magnitude and distribution of adjustment costs For concreteness,

---

[4] In this context, the term „mixed complementarity problem“ (MCP) is straightforward: „mixed“ indicates that the mathematical formulation is based on weak inequalities that may include a mixture of equalities and inequalities; „complementarity“ refers to complementary slackness between system variables and system conditions.

exogenous policy constraints such as stabilization or temperature targets will bind future economies the more, the higher projected BaU growth in GHG emissions. Substantial differences in model-based analysis can often be traced back to different assumptions about the reference case. Yet, the central role of baseline assumptions in general receives little attention in the literature. Regarding long-term climate policy analysis, the issue of baseline projections becomes very critical in view of the tremendous uncertainties regarding BaU developments over several decades. Not only is there the question why one baseline should be preferable over another, but often projections based on partial equilibrium judgements/analysis stand out for large internal inconsistencies.

Against this background, a careful documentation of the baseline calibration is a conditio-sine-qua-non for the interpretation of results. In this section, we first describe the consistency conditions to calibrate a dynamic model along the global steady-state growth path. Second, we lay out a pragmatic approach how we can accommodate differential growth rates across various regions while avoiding potentially large deterioration in the terms of trade through the model horizon. Third, we sketch how exogenous projections on GHG emissions (i.e. in particular fossil fuel use) can be incorporated in a plausible manner along with projections of GDP growth rates. Fourth, we outline the inclusion of non-CO2 GHG abatement possibilities. Fifth, we describe the concrete parameterization of the intertemporal model that will be used for impact analysis of GHG alternative stabilization scenarios.

3.1. Steady-state calibration

The challenge in setting up a dynamic model is to reconcile the dynamic equilibrium conditions in terms of the benchmark data that incorporates base-year values for capital earnings, investment, and current account. Along the steady-state all quantities increase at the exogenous growth rate, while all prices expressed as present values decline at some interest rate (reflecting the pure rate of time preference). Steady-state growth implies mutual consistency of growth and interest rates together with capital earnings and investment values. However, in the benchmark data set, the steady-state conditions are typically not satisfied for arbitrary assumptions on dynamic parameters such as the growth, interest, and depreciation rates. If we assume plausible values for the latter parameters, the steady-state capital values share implied by steady-state growth, e.g., differ substantially from reported base-year values. To assure consistency and avoid re-calibration of the investment demand vector, one can calibrate capital and other factor shares to match the capital values share implied by the base year investment. For identical growth rates across all regions, this data adjustment assures consistency to steady-state growth.

3.2. Differential growth rates

In applied policy analysis, growth rate projections typically differ across regions. In this situation, the baseline equilibrium must be computed. When regions grow at different rates, there may be a substantial induced change in the terms of trade, and this makes it difficult to calculate a baseline growth path that matches economic targets such as investment and consumption. A pragmatic means of dampening changes in terms of trade for differentiated baseline growth rates is to adjust Armington share parameters over time in proportion to potential GDP. As a country grows faster, it is assumed that this produces an autonomous (non-price induced) change in the demand for the country's goods both in the home country as well as for the rest of the world. Since there is no change in the efficiency as a result of these demand adjustment, at base year prices, the cost of a unit of the aggregate commodity remains unchanged, even though there may be a substantial difference in the relative growth rates across countries. A final problem after the adjustment of Armington demand functions is related to assets rather than terms of trade and becomes evident in deviations between baseline and base year consumption. This reflects an inherent difficulty in setting up an equilibrium growth model in which the base year is not on a steady-state growth path. The level of net borrowing does not reflect earnings on assets - some of these capital flows represent ongoing changes in net asset positions as countries move toward the long-run equilibrium. In order to exactly replicate the base year consumption level, the level of net assets in the base year can be treated as a variable which is computed endogenously. These values are adjusted so as to produce a common base year consumption level in all regions.

3.3. Energy (Carbon) intensities

Standard baseline projections for climate or energy policy analysis include not only exogenous information on future GDP, but also detailed accounts on fossil fuel use, world market energy prices, and CO_2 emission profiles. In order to incorporate the energy data, we perform a two-step recalibration. First, we use the baseline intensities for fossil fuel demands to re-scale the baseline cost shares in the production of the electric and non-electric energy aggregates. In order to preserve the initial *total* costs per unit of production, we inversely adjust the capital cost shares, meaning that energy efficiency improvements are not costless but are linked to the increased use of capital services. Within the BaU re-calculation, we endogenously adjust the resource endowments of fossil fuels to calibrate the model to given exogenous target prices for fossil fuels. In a second step, we then recalibrate fossil fuel supply functions locally to match exogenous estimates of fossil fuel supply elasticities.

3.4. Parameterization

As is customary in applied general equilibrium analysis, base year quantities and prices – together with exogenous elasticities – determine the parameters of functional forms. The most comprehensive base year statistics on global trade and energy use are provided by the GTAP5 database that features consistent accounts of regional production and consumption, bilateral trade and energy flows for up to 66 countries/regions and 57 commodities in the year 1997 (Dimaranan and McDougall 2002).

Considering the regional resolution of our climate policy analysis, the binding constraint comes from the availability of long-term baseline projections. Here we make use of the WEC/IIASA database that includes projections for GDP, fossil fuel use and carbon as well as methane emission profiles up to 2100 for eleven geo-politically important world regions and six alternative long-term futures (WEC/IIASA 1998). In order to reduce the computational burden for the numerical analysis, we have further aggregated the eleven regions to seven model regions. The sectoral aggregation in the model has been chosen to distinguish carbon-intensive sectors from the rest of the economy as far as possible given data availability. It captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across carbon-intensive goods. The energy goods identified in the model are coal, natural gas, crude oil, refined oil products and electricity. Important carbon-intensive and energy-intensive non-energy industries that are potentially most affected by carbon abatement policies are aggregated within a composite energy-intensive sector. In order to keep track of the most important source for methane emissions, agriculture forms an explicit sector. The remaining manufacturers and services are aggregated to a composite industry that produces a non-energy-intensive macro good. The primary factors in the model include labor, physical capital and fossil-fuel resources. Table 1 summarizes the regional, sectoral, and factor aggregation of the model.

Among the six possible futures that are provided in the WEC-IIASA database, we use scenario B as our reference case. Scenario B is based on a cautious approach to technological change and energy availability as well as, modest economic growth. Table 2 provides an overview of central indicators for our reference scenario.

Table 1: Model dimensions

Production Sectors	Countries and Regions
Energy	North America (USA and Canada)
Coal	Western Europe
Crude oil	Pacific OECD (Japan, Australia, New Zealand)
Natural gas	Newly independent states of the former Soviet Union
Refined oil products	Central and Eastern Europe
Electricity	Africa, Latin America, and Middle East
Non-Energy	Asia
Agricultural production	
Energy-intensive sectors	*Primary factors*
Other manufactures and services	Labor
Savings good	Capital
	Fixed factor resources for coal, oil and gas

Table 2: Main characteristics of WEC-IIASA scenario B (WEC/IIASA 1998)

	Scenario B (“Middle course”)
Carbon emissions (GtC)	9.6 (in 2050) - 11.4 (in 2100)
World economic growth	2.2 % p.a.
Environmental taxes	No
Carbon constraints	No

4. Non- CO_2 Abatement Options

CO_2 is the major anthropogenic greenhouse gas contributing to global warming. However, other greenhouse gases including CH_4, N_2O, and a number of industrial process gases are also relevant to climate change. In our multi-gas simulations below we track energy related emission of CO_2 and energy and non-energy emissions of CH_4 as the most important non-CO_2 greenhouse gas. We endogenously determine the level of CO_2 and CH_4 emissions thereby taking into account the various sources of anthropogenic CH_4 emissions and the technological options to abate them.

Agriculture is a principal source of CH_4 emissions. Especially the livestock sector contributes through enteric fermentation and the (anaerobic) decomposition of manure to the amount of CH_4 emissions from the agriculture sector. An important source of CH_4 emissions in agriculture is rice cultivation. Fugitive CH_4 emissions from natural gas and oil systems, especially from the production, processing, transmission and distribution of natural gas are considerably large. Less important are agricultural residue burning. Coal production (mining and post-mining activities) also produces CH_4 emissions through the process of coal formation which results in CH_4 that is stored in the coal. Municipal and industrial waste (solid waste landfilling and wastewater treatment) leads to anaerobic decomposition of waste and thereby CH_4 emissions. Other CH_4 emission sources include, e.g., stationary and mobile combustion and biofuel combustion.

Table 3: CH_4 sources, emission baseline and corresponding model sectors

CH_4 emission sources	EPA Baseline 2010 (in MMTCE)	Model sector
Rice cultivation	187.4	Agricultural Production
Enteric fermentation	557.9	
Manure management	65.3	
Biomass burning (agricultural residue burning)	75.1	
Coal production (underground and surface mining and post-mining)	140.9	Coal
Crude oil production	19.4	Crude oil
Natural gas systems (production, processing, transmission and distribution)	316.3	Natural gas
Industrial sewage (wastewater)	174.3	Energy-int. sectors
Domestic sewage (wastewater)		Household
Landfills of solid waste	239.0	
Stationary and mobile combustion	19.2	
Biofuel combustion	64.1	
Other	5.5	

Table 3 provides an overview of the CH_4 sources, baseline emissions in 2010 provided by the United States Environmental Protection Agency (EPA) (*see "Reference" in this special issue*) and the mapping of CH_4 sources to the sectors incorporated in our model.

Carbon emissions are directly linked to the combustion of fossil fuels. The key to lower carbon emissions is thus the reduction of fossil fuel combustion. In contrast, emissions of other GHG gases cannot, in general, be tied in fixed proportions to activity (use) as there are technical possibilities to reduce emissions per unit of activity. EPA provides bottom-up estimates of the abatement potential for CH_4 emission sources and the associated marginal abatement costs (*see "Reference" in this special issue*). There are regional marginal abatement cost curves (MAC) available for different activities: rice cultivation, enteric fermentation, manure management, coal production, crude oil production, natural gas systems and landfills of solid waste. More than 80 % of total anthropogenic CH_4 emission are hence supplemented with engineering information about technical options for potential emission abatement. Figure 3 illustrates marginal abatement cost curves for different CH_4 emission sources in the year 2010.

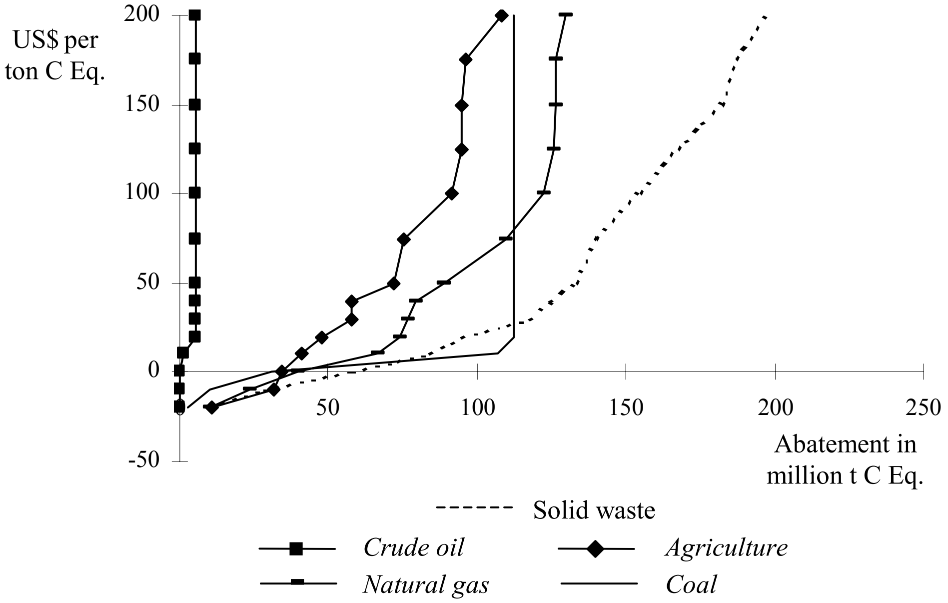

Figure 3: Global marginal abatement cost curves for CH_4 emission sources in 2010 (Source: "Reference" in this special issue)

To incorporate the cascaded marginal abatement cost curves for CH_4 in each sector and region of our model, we first compute an equilibrium path of the counterfactual GHG abatement scenario without CH_4 abatement options. Next, we evaluate the solution with respect to carbon prices. We then assume that all potential cost-effective CH_4 abatement options in each sector and region are implemented. We thus get a point estimate of CH_4 abatement levels, marginal cost of abatement, and the average cost increase of CH_4 abatement, whereby the latter is given by the area under the marginal abatement cost curve divided by the sectoral activity level. We then calculate the new temperature profile with the adjusted CH_4 emissions. Using the new equilibrium path, we can update the CH_4 abatement and cost fractions. The iterative CH_4 abatement algorithm converges quickly to a stable solution.

5. The Climate Sub-Module

In order to assess climate change policy options we combine economic aspects of climate change with scientific knowledge of the dynamics of climate change in an integrated assessment model. Climate-change modeling is introduced through the geophysical module of the RICE-99 (Regional Integrated model of Climate and the Economy) model (Nordhaus and Boyer 2000). It contains a number of geophysical relationships that link together the different forces affecting climate change. The geophysical relations are simplified representations of more complex models and give a reduced form description of emissions, concentrations, and globally averaged temperature change. Economic activity leads to CO_2 emissions which affect climate through their radiative forcing. The accumulation and transportation of CO_2 emissions is modeled as a linear three-reservoir approach calibrated to existing carbon cycle models. The three reservoirs represent the atmosphere, a quickly mixing reservoir in the upper oceans together with the short-term biosphere, and the deep oceans. The accumulation of CO_2 emissions in the atmosphere leads to an increase in radiative forcing. This relationship is derived from large-scale climate models: The radiative forcing equation includes the forcings of other greenhouse gases (CH_4, N_2O, CFCs and ozone) and aerosols as an exogenous component. The climate-change equations link radiative forcing and climate change based on the three-box climate model representation. An increased radiative forcing warms the atmosphere with some time lag due to the thermal inertia of the different ocean layers.

In the RICE-99 environmental module only CO_2 is endogenously modeled. Other greenhouse gases and their radiative forcings are assumed to be exogenous. For our multi-gas analysis we endogenize CH_4 as the most important non-CO_2 greenhouse gas. The calibration of the extended environmental module is based on the MERGE climate module (Manne et al. 1994). Methane emissions result from different sources and are linked to economic activities in the economic model. These emissions build up a CH_4 stock. The base year stock of methane is assumed to be 4.850 billion tons of CH_4 of which 60 % are subject to decay with a yearly retention factor of 8.3 % reflecting the atmospheric lifetime. The increase in the stock of methane leads to an increase in the radiative forcing of methane which is proportional to the logarithm of the ratio of the current to the initial level and takes into account the interaction effects of CH_4 and N_2O. The aggregate radiative forcing is again the sum of the radiative forcing for CO_2, CH_4 and the other exogenous forcings. The temperature equations remain unchanged.

Our algorithm for computing "when-efficient" tax profiles involves iterative computation of the numerical derivatives of temperature with respect to greenhouse gas emissions (CO_2 and CH_4 in our case). It turns out that these partial derivatives are fairly stable, which makes it possible to compute time-efficient tax profiles without resorting to an optimizing framework.

Due to the large uncertainties in damage estimates for climate change, we do not attempt to translate global warming into market impacts (such as productivitiy changes, capital depreciation) and non-market impacts (such as biodiversity losses, natural disasters) (Manne et al., 1995): There is only a one-way link between economic variables and biophysical variables. As a consequence, the welfare analysis is solely driven by economy-wide adjustment costs and restrictive GHG emissions control policies are necessarily welfare decreasing (in the absence of major second-best effects due to initial market distortions). The coupling of the economic system and climate system for our integrated CGE assessment is depicted in Figure 4.

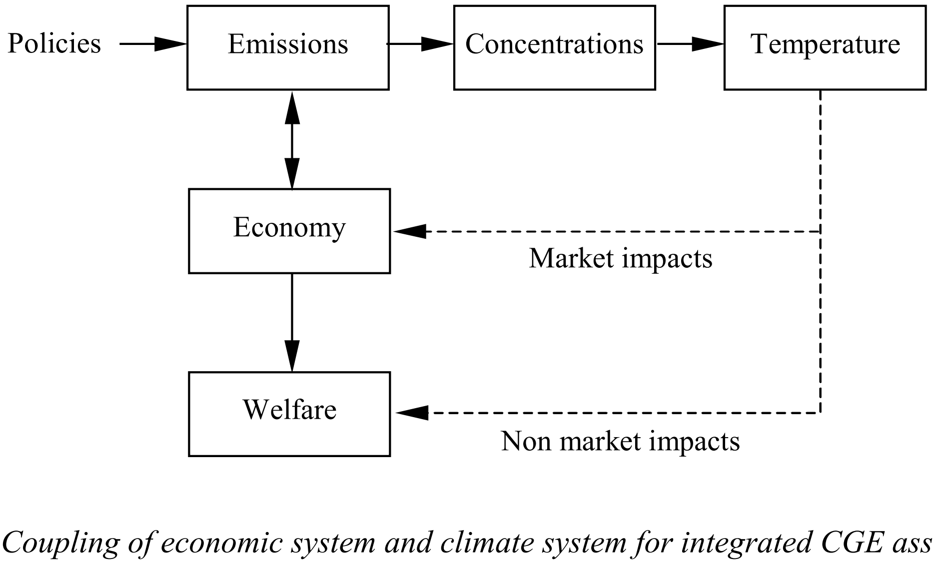

Figure 4: Coupling of economic system and climate system for integrated CGE assessment

6. Scenarios and Results

We distinguish two different climate control schemes. The first control scheme (*Target*) aims at stabilizing the long-term global temperature at an exogenously given level from 2100 onwards. Such a policy reflects the precautionary principle adopted by the UNFCCC to prevent global mean temperature rising beyond a certain threshold that could imply dangerous anthropogenic interference with the climate system. In our central case setting, temperature may not increase more than 90 % of the BaU temperature increase in 2100. The second control scheme (*Rate*) imposes an additional constraint on the rate of temperature change in addition to the long-term temperature stabilization target. This scenario reflects concerns that damages might not be only dependent on absolute temperature change but also on the rate of temperature change (see e.g. Peck and Teisberg, 1994, Alcamo and Kreileman 1996).[5]

In order to assess the importance of "what"-flexibility we combine each of the two control schemes with two alternative assumptions on the scope of greenhouse gases that are explicitly included. Variant CO_2 covers the case where only carbon emissions are subject to direct emission control measures. Variant *Multigas* explicitly includes various greenhouse gas emissions (in our case: CO_2 and CH_4) within the abatement strategy. In total, we thus obtain four scenarios whose characteristics are summarized in Table 4. Across all scenarios, comprehensive "where"-flexibility applies, i.e. emissions will be abated where it is cheapest.

Table 4: Central case scenarios

	Control scheme	Emission s.t. control policy
CO_2-T_{Target}	Temperature target	CO_2 only
Multigas-T_{Target}	Temperature rate	CO_2 and CH_4
CO_2-T_{Rate}	Temperature target	CO_2 only
Multigas-T_{Rate}	Temperature rate	CO_2 and CH_4

Abstracting from external costs of climate change, we simply investigate the least-cost way to satisfy external policy constraints with respect to the choice of the control scheme and the scope of GHG emissions covered. Our scenarios are thus based on a cost-effectiveness paradigm rather than comprehensive cost-benefit analysis. Without accounting for benefits

---

[5] We approximate an upper bound on the decadal rate of change by specifying a set of temperature targets for each decade beginning in 2030.

from emission abatement, compliance to the exogenous emission control scheme necessarily involves global adjustment costs vis-à-vis the unconstrained business-as-usual.[6]

In the exposition of results from our large-scale multi-sector, multi-region CGE model PACE, we focus on global cost implications across the different scenarios. At the regional level, compliance costs will to a large extent depend on the allocation of the (endogenous) global emission budget which emerges from the respective emission control policies. This leads to the fundamental issue of burden sharing, i.e. the question how abatement duties - or likewise emission entitlements – shall be allocated across countries. This issue has already dominated climate negotiations under the Kyoto Protocol and proved extremely difficult to resolve. We do not want to enter the controversial and highly subjective debate on equity principles here and adopt the economist's typical device to separate efficiency from equity considerations (handling some exogenous distributional objective by means of hypothetical lump-sum transfers).

Note that, abstracting from secondary income effects, the initial emission entitlement does not affect global efficiency given full flexibility.[7]

Table 5 reports the global compliance costs across our four central scenarios. The qualitative results confirm basic economic intuition: (i) imposition of a decadal rate constraint on top of the temperature target will be more restrictive for the global economy and thus generate larger adjustment costs, and (ii) "what"-flexibility in terms of a multigas abatement approach reduces overall compliance costs for a given control scheme vis-à-vis a CO2-only strategy. The concrete quantitative figures show that global costs are relatively moderate ranging from a loss in lifetime BaU consumption of 0.01 % (scenario: *Multigas-*T_{Target}) up to 0.22 % (scenario: *Multigas-*T_{Rate}). However, the differences across scenarios are quite substantial. First, we see that hedging against "larger" decadal rates of temperature change is quite expensive – in fact the compliance costs are an order of magnitude higher as compared

---

[6] In principle, second-best effects such as the interaction of emission control schemes with existing distortionary taxes might offset the direct emission control costs yielding a double dividend (see Goulder 1995, Bovenberg 1999). In our analysis, we deliberately neglect the incorporation of major initial distortions owing to the aggregate nature of our global model that makes it difficult to reflect specific tax and transfer systems as well as institutional constraints – such as labor market rigidities – in an appropriate manner.

[7] In our simulations we assume that in any period the BaU carbon emissions are scaled uniformly across regions to result in the (endogenous) global GHG emissions that are consistent with the temperature constraint. From an equity perspective, such an entitlement rule would reflect a sovereignty approach, where projected BaU emissions constitute a status quo right.

to the respective scenarios that only involve a long-term temperature target. Second, “what”-flexibility provides substantial efficiency gains cutting down the compliance costs vis-à-vis a CO2-only strategy by roughly a half.

Table 5: Global adjustment costs expressed as Hicksian equivalent variation (HEV) in income (% present value of BaU consumption).

	Temperature target		Decadal rate	
	CO_2-T_{Target}	*Multigas-T_{Target}*	*CO_2-T_{Rate}*	*Multigas-T_{Rate}*
	-0.02	-0.01	-0.22	-0.11

Figure 5 depicts the trajectory of the global mean temperature for the central case scenarios. Policies that only aim at limiting the increase in global mean temperature in 2100 at 90 % of the BaU value involve little temperature decreases vis-à-vis the business-as-usual until the mid of the century. Policies that in addition limit the decadal rate of temperature change are much more restrictive and involve distinct temperature decreases from BaU already in initial periods.

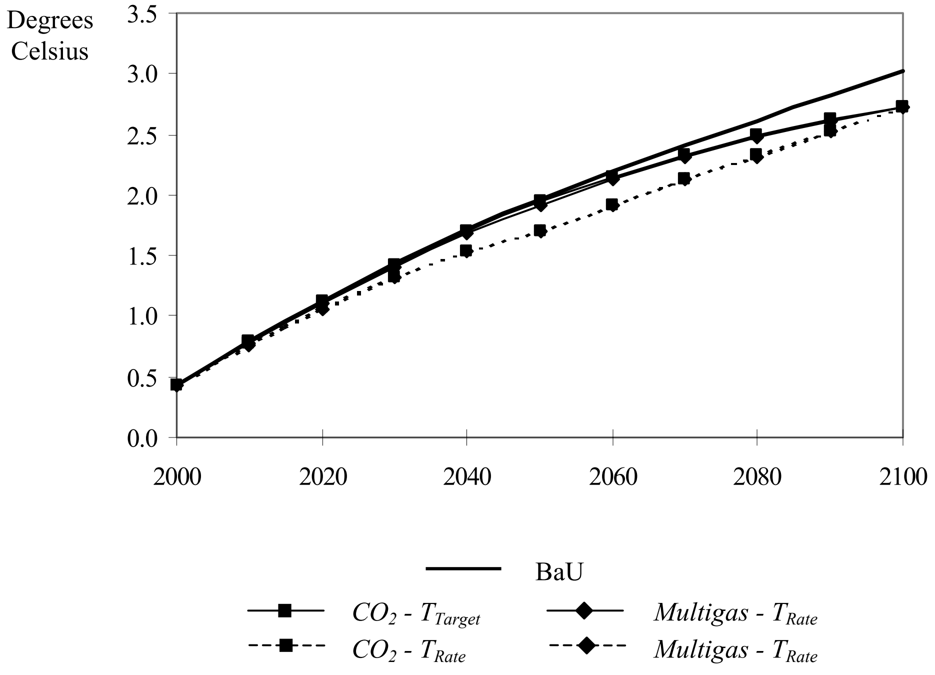

Figure 5: Global mean temperature (degrees Celsius)

Figure 6 illustrates the carbon emission profiles that emerge from the imposition of temperature targets and rate constraints. We see that the long-term temperature targets without decadal rate constraint allow for substantial increases in emission levels from current levels to the mid-century.

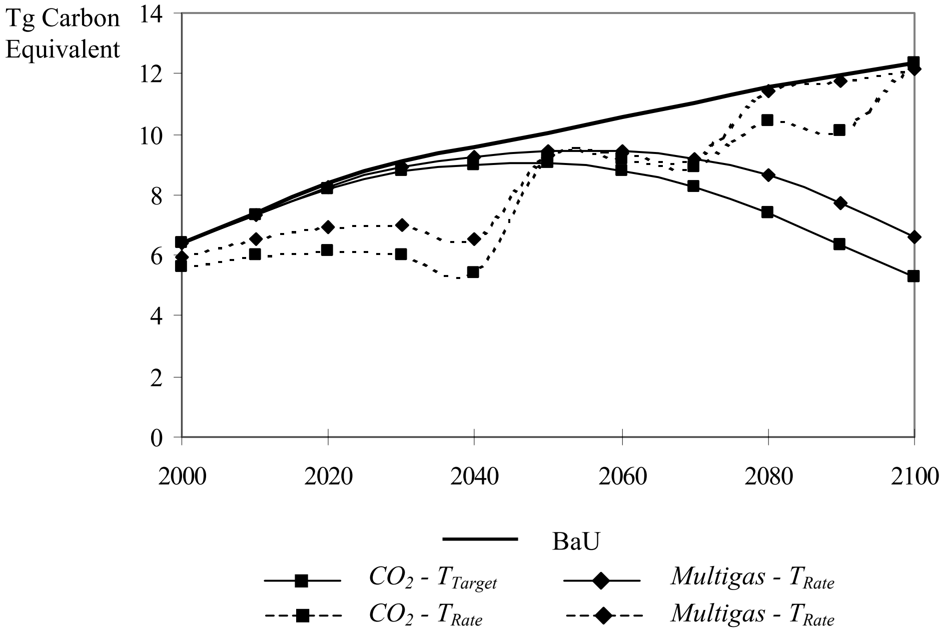

Figure 6: CO_2 Emissions from fossil fuels (Tg of C eq.)

The cutback requirements from BaU are relatively modest till 2050 but thereafter emissions must be reduced substantially to achieve the temperature target. In other words: abatement is shifted to the second half of the century where costs in present value terms simply decrease by discounting. Additional rate constraints imply larger cutbacks from BaU levels already in the initial decades. The climate dynamics reflecting past emissions then allow to increase emissions from 2040 onwards with a steep increase in the period between 2040-2050, some stable emission levels between 2050-2070 and a final increase towards BaU emission levels at the end of the century. The discontinuous step-function type emission trajectories for the scenarios with decadal rate constraints reflect the discrete bounds on rate increase. Due to the latter, there is no leeway for smoothing the carbon profile as is the case for the target-only scenarios. “What”-flexibility allows for higher CO_2 emissions for both climate control schemes (*Target* and *Rate*) since CH_4 abatement will be undertaken whenever it is cheaper.

The carbon emission profiles for the different scenarios are an indicator for the potential magnitude of compliance costs. The less carbon emissions must be cut back and the later in time abatement takes place the less costly the control scheme is – not surprisingly the comparison of profiles along these lines reveal the *Multigas*-T_{Target} as the least-cost scenario.

Figure 7 shows the magnitude of carbon taxes that would be required to achieve the long-term temperature target and - for scenarios *CO_2-T_{Rate}* and *Multigas-T_{Rate}* - to meet the rate constraints.

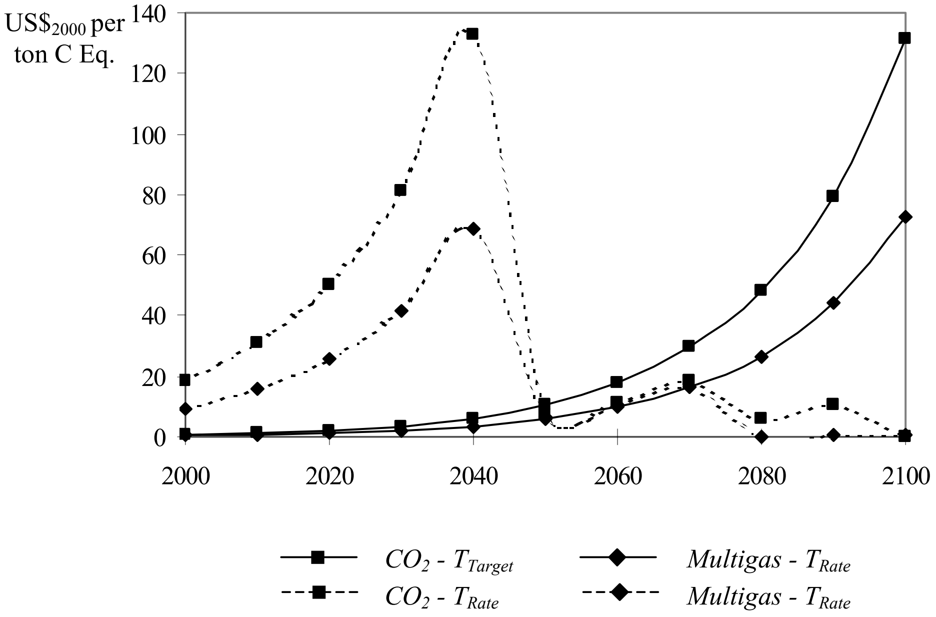

Figure 7: Incremental value of carbon permit / carbon tax (US$$_{2000}$/metric ton C Eq)

The course of the tax trajectories mirror the characteristics of the emission trajectories. When climate policies only aim at long-term temperature targets there is a continuous increase in carbon taxes towards the end of the century reflecting economic rationality to postpone abatement as long as possible. Rate constraints trigger very high shadow prices in the initial periods whereas towards the end of the model horizon prices become very small or even zero (as rate constraints may no longer be binding).

Figure 8 illustrates the tradeoffs between CO_2 and CH_4 based on efficiency prices that is the ratio of shadow values for these gases with respect to the long-term temperature target (scenario: *Multigas-T_{Target}*). As indicated by the natural science of the climate system this ratio increases over time since the impact of an additional emission unit CH_4 on the global mean temperature goes up relatively to the impact of an additional emission unit of CO_2. With its relatively short lifetime, the value of CH_4 increases as one approaches the temperature ceiling. The kink in 2080 reflects the "break-point" where the shorter lifetime of CH_4 vis-à-vis CO_2 does no longer matter with respect to the terminal temperature target. Figure 8 highlights the pitfalls of the Global Warming Potential (GWP) approach for establishing equivalence among greenhouse gases. Price rations may vary substantially over time (in addition they are sensitive to the ultimate temperature goal – see Manne and Richels 2001).

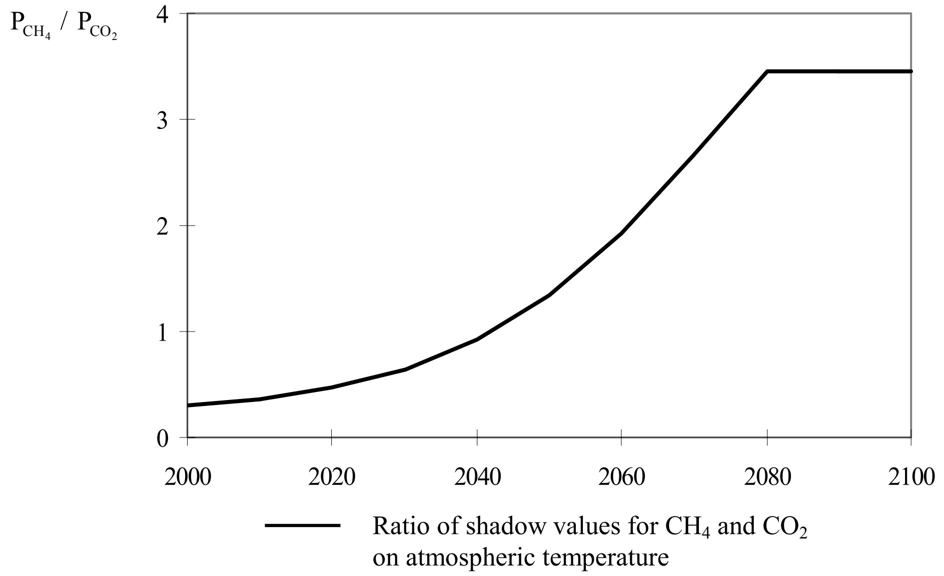

Figure 8: Ratio of shadow values for CH_4 and CO_2 on atmospheric temperature

7. Conclusions

In this paper, we have investigated the importance of "what"-flexibility for alternative emission control schemes that prescribe long-term temperature targets and eventually impose additional constraints on the rate of temperature change. In line with previous analysis, we find that "what"-flexibility can provide substantial global efficiency gains as cost-efficient abatement options for non-CO_2 gases are directly taken into account. In our simulations, we have identified very large insurance premia when hedging against too rapid rates of temperature increase. We have also highlighted the shortcomings of the GWP approach to represent the contribution of different greenhouse gases to radiative forcing.

From a methodological point of view, the primary objective of our paper has been to lay out a multi-sector, multi-region CGE model PACE that entails a careful baseline calibration and provides a self-consistent simple representation of the connection between greenhouse gas emissions and climate change (radiative forcing and temperature).

We close with several caveats. Although our model captures important economic aspects of long-term emission control schemes, it is only a crude approximation of the real world's technologies, preferences, endowments, etc. This applies in particular to longer-term analysis where substantial uncertainties about the future economic development prevail. Furthermore, our reduced from representation of the climate dynamics is very simplistic. Against this background we caution against too literal an interpretation of our numerical results.

Acknowledgements

Financial support from the European Commission under the Grant Agreement "Network Activity on non-CO2 Greenhouse Gases" (SUB/02/339507/E1) is gratefully acknowledged. The ideas expressed here are those of the authors, who remain solely responsible for errors and omissions.

References

Alcamo, J. and G. J. J. Kreileman (1996), "Emission scenarios and global climate protection.", *Global Environmental Change*, 6(4), 305-334.

Armington, P. A. (1969), "A Theory of Demand for Products Distinguished by Place of Production", *IMF Staff Papers*, 16 (1), 159–178.

Bergman, L. (1990), "The Development of Computable General Equilibrium Models", in: L. Bergman, D. W. Jorgenson and E. Zalai (eds), *General Equilibrium Modeling and Economic Policy Analysis*, Oxford: Blackwell, 3–30.

Böhringer, C. and T. F. Rutherford (2002), "Carbon Abatement and International Spillovers", *Environmental and Resource Economics*, 22 (3), 391-417.

Brooke, A., D. Kendrick and A. Meeraus (1996), *GAMS: A User's Guide*, Washington DC: GAMS Development Corp.

Bovenberg, A. L. (1999), "Green Tax Reforms and the Double Dividend: An Updated Reader's Guide", *International Tax and Public Finance*, 6, 421–443.

Dirkse, S. and M. Ferris (1995), "The PATH Solver: A Non-monotone Stabilization Scheme for Mixed Complementarity Problems", *Optimization Methods and Software*, 5, 123–156.

Dimaranan, B. V. and R. A. McDougall (2002), *Global Trade, Assistance, and Production: The GTAP 5 Data Base*, Centre for Global Trade Analysis, Purdue University.

Grubb, M., J. Edmonds, P. ten Brink and M. Morrison (1993), "The Costs of Limiting Fossil-fuel CO_2 Emissions: A Survey and Analysis", *Annual Review of Energy and Environment*, 18, 397–478.

Gollier, C., B. Jullien, and N. Treich (2000), "Scientific Progress and Irreversibility: An Economic Interpretation of the Precautionary Principle", *Journal of Public Economics*, 75, 229-253.

Goulder, L. H. (1995), "Environmental Taxation and the Double Dividend: A Reader's Guide", *International Tax and Public Finance*, 2, 157–183.

IPCC (2001), "Climate Change 2001: Mitigation", Working Group III, Third Assessment Report, Section 1.3.1, Cambridge University Press, Cambridge.

Lau, M. I., A. Pahlke and T. F. Rutherford (2002), "Approximating Infinite-horizon Models in a Complementarity Format: A Primer in Dynamic General Equilibrium Analysis", *Journal of Economic Dynamics and Control*, 26(4), 577-609.

Manne, A. and R. Richels (2001), "An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases", *Nature*, 410, 675-677.

Manne, A., R. Mendelsohn, and R. Richels (1995), "MERGE. A model for evaluating regional and global effects of GHG reduction policies", *Energy Policy*, 23(1), 17–34.

Manne, A., R. Mendelsohn and R. Richels (1994), "MERGE: A Model for Evaluating Regional and Global Effects of GHG Reduction Policies", in: N. Nakicenovic, W. Nordhaus, R. Richels and F. Toth (eds.), "*Integrative Assessment of Mitigation, Impacts, and Adaptation to Climate Change*", CP-94-9, International Institute for Applied Systems Analysis, Laxenburg, Austria, 143-172.

Nordhaus, W. D. and J. Boyer (2000), *Warming the World : Economic Models of Global Warming*, Cambridge, Mass.: MIT Press.

Peck, S. C. and T. J. Teisberg (1994), "Optimal Carbon Trajectories when Damages Depend on the Rate or Level of Global Warming", *Climatic Change*, 28, 289-314.

Rutherford, T. F. (1995), "Extensions of GAMS for Complementarity Problems Arising in Applied Economics," *Journal of Economic Dynamics and Control*, 19(8), 1299-1324.

Rutherford, T. F. (1999), "Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax", *Computational Economics*, 14, 1–46.

Takayama, T. and G. G. Judge (1971), "Spatial and Temporal Price and Allocation Models", Amsterdam: North-Holland Publishing Co.

Uzawa, H. (1969), "Time Preference and the Penrose Effect in a Two Class Model of Economic Growth," *Journal of Political Economy*, 77, 628-652.

WEC [World Energy Council] / IIASA [International Institute for Applied Systems Analysis] (1995), "Global Energy Perspectives to 2050 and Beyond", Cambridge: Cambridge University Press.

Weyant, J. (ed.) (1999), "The Costs of the Kyoto Protocol: A Multi-Model Evaluation", *The Energy Journal*, Special Issue.