Contraction and Convergence of Carbon Emissions

An Intertemporal Multi-Region CGE Analysis

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Abstract

In the context of climate protection policy it has been suggested that global CO_2 emissions should be reduced significantly (*contraction*) and that per capita emissions should gradually be equalized across countries (*convergence*). This paper uses an inter-temporal multi-region computable general equilibrium model of the world economy to assess the economics of "Contraction and Convergence" (C&C). In comparing a regime of tradable and non-tradable emission rights for implementing C&C we find that international emissions trading increases crucially the political feasibility of the C&C proposal. The reason is that the distribution of the total efficiency gains from permit trading not only improves the economic well-being of all regions as compared to strictly domestic action, but in particular raises economic welfare of major opponents to carbon restrictions from the developing world even beyond non-abatement baseline levels. A decomposition of the general equilibrium effects associated with C&C shows that changes in the terms of trade constitute a key determinant of the overall welfare effects.

Key words: computable general equilibrium modeling, climate protection, emissions trading

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1. Introduction

There is meanwhile common scientific agreement that mitigation of climate change requires a substantial reduction of anthropogenic greenhouse gas emissions. In its most recent assessment, the Intergovernmental Panel on Climate Change (IPCC) states that in order to avoid a substantial increase of the global mean temperature by the end of the 21st century, global emissions will have to be reduced by up to one half by 2100 (UNEP 2001).[1] In a similar vein, there have been several proposals in the literature on global emission abatement policies since the early 1990s (Grubb and Sebenius 1992, Shue 1993, Welsch 1993), in which the emphasis is placed not only on a significant *contraction* of anthropogenic CO_2 emissions, but also on an equitable per capita distribution of the resulting global carbon budget. The latter implies a transition to a point (c*onvergence*) where future entitlements to emit will have become proportional to population.

The uniform per capita allocation of emission rights reflects egalitarianism in the sense that all people have inherently an equal right to pollute. The egalitarian criterion per se has a strong philosophical appeal. However – under contraction of the global carbon budget – it is unlikely to be acceptable for industrialized countries with currently high per capita emissions unless the transition path allows for long-term "smooth" adjustment towards the terminal point.

Equity considerations are not only ethically founded; they also conform to the idea that equity might "serve a positive role as a unifying principle that facilitates an international greenhouse warming agreement" (Rose et al. 1998). Many analysts of the issue have concluded that greater cooperation is likely to be forthcoming if the cooperation agreement is perceived to be fair (see e.g. Morrisette and Plantinga 1991, Bohm and Larsen 1994). On part of the developing world, fairness comes ultimately down to an equal per capita allocation of emission rights (Rose et al. 1998). In fact, convergence towards equal per capita emission rights in the course of time was explicitly mentioned in an early draft of the Climate Convention (Beckerman and Pasek 1995), but later this provision was replaced by the weaker formulation that "Parties should protect the climate system ... on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities" (UNFCC 1992, Article 3, paragraph 1). Nevertheless, equal per capita entitlements, which

[1] In contrast to these long-term requirements, the provisions of the Kyoto Protocol are of a relatively short-term nature (2008-2012). The Kyoto emission limits refer only to the industrialized countries and will not prevent global carbon emissions to grow significantly for reasonable baseline assumptions of economic development and future fossil fuel consumption in developing countries.

correspond to the justice principle of "equality of resources" is the fair division criterion most often mentioned in the literature (see Bertram 1992; Kverndokk 1995).

Apart from equity considerations, the opportunities for cost effectiveness of global abatement policies play another major role in climate policy negotiations. International emissions trading will reduce the global costs of emission abatement to the extent that it exploits differences in marginal abatement costs across regions. However, apart from moral objections ("opportunity for polluters to buy themselves out"), more pragmatic concerns refer to potentially high transaction costs of certification, verification and monitoring of international emissions trading.

This paper uses a dynamic multi-region general equilibrium model of the world economy to investigate the economic impacts of "Contraction and Convergence" under the two extreme assumptions for tradability of emission entitlements, i.e. no emissions trading versus global trade in permits.

From a policy point of view, our most relevant conclusion is that "Contraction and Convergence" could only serve as a unifying concept to operate climate protection in the long run *if* emission entitlements are globally tradable. The reason is not only that emissions trading significantly reduces the overall costs of stringent emission abatement. More importantly, the distribution of efficiency gains implied by international emissions trading makes the "Contraction and Convergence" proposal rather attractive for the developing world while assuring that the developed world still benefits considerably as compared to the no-trade case. In fact, international emissions trading under "Contraction and Convergence" allows most developing countries to improve their economic welfare beyond business-as-usual; in other words, even when we neglect the potential benefits from mitigation of global warming, most developing countries are better off from global carbon abatement than without climate protection.

From a methodological point of view, our decomposition of general equilibrium effects shows that changes in terms of trade constitute a key determinant of the overall welfare effects implied by "Contraction and Convergence". Any analytical framework that disregards such spillovers is therefore inappropriate as a methodological tool.

The remainder of this paper is organized as follows. In section 2 we explain how the C&C formula is operated to derive the emission budgets of regions along the time-path; we also sketch the abatement policies to be analyzed in the current paper. In section 3 we describe the basic features and the parameterization of our modeling framework. In section 4 we present results. In section 5 we offer policy conclusions.

2. Operating "Contraction and Convergence"

A. Permit Allocation Formula

With respect to "Contraction", we assume that global carbon emissions are to be reduced by 25 percent in 2050 relative to1990 emission levels reflecting most recent requests by the IPCC on long-term abatement requirements (UNEP 2001). In accordance with "Convergence", it is postulated that each person in the world should have an equal share in the resulting stock of carbon emission rights in 2050. The emission quotas for the period before 2050 should reflect differences in present per capita emissions, in order to facilitate smooth adjustment of countries that have currently very high per-capita emissions.

More specifically, we assume that the allotment of long-term carbon rights comes into force by the year 2010.[2] Then the per capita emission rights of country *i* in year *t*, $z_i(t)$, should be a weighted average of per capita emissions in 2010 and the uniform per capita right valid in 2050:

$$z_i(t) = \frac{40-(t-2010)}{40} \cdot z_i(2010) + \frac{(t-2010)}{40} \cdot \bar{z}$$

where: $z_i(2010)$ denotes the per capita emissions in 2010 in country *i*, and

$\bar{z}$ refers to the uniform per capita emission right in 2050.

The total carbon limit $CARBLIM_i(t)$ for a country in a certain year is obtained by multiplying the per capita emission right by the country's population $POP_i(t)$ in that year:

$$CARBLIM_i(t) = z_i(t) \cdot POP_i(t).$$

Of course, in implementing this formula, it is important to use population projections fixed ex ante, in order to avoid incentives for population growth. Adding the carbon limits across countries defines the global carbon limit.

This procedure gives a gradual adjustment in both *total* emissions and in the *distribution* of emission rights across countries, in line with the contraction and convergence paradigm.

Table 1 summarizes the per capita endowment with carbon emission rights across regions emerging from the C&C-formula. The overall carbon limit in 2050 together with the population projections implies a reduction of world per-capita emissions from 1.07 tons of carbon in 2000 to 0.48 tons in 2050. By definition of our C&C-formula the terminal value in

[2] The choice of 2010 as the starting year for global emission reduction reflects the idea that some time will be needed to achieve such a substantial international agreement and that its provisions will not enter into force instantaneously.

2050 is identical for all regions. The initial value as of 2000, however, shows a tremendous dispersion, ranging from 0.21 tons for Sub-Saharan Africa to 5.23 tons for North America.

This dispersion reflects the current "inequities" in per capita emissions between the industrialized regions and developing countries. It should be noted, however, that all regions - except for Sub-Saharan Africa and India - have to cut back their emissions per capita (of course, by varying degrees) relative to current levels.

Table 1: Per capita emission endowments by region (in tons of carbon per capita)

Year	2000	2010	2020	2030	2040	2050
Sub-Saharan Africa (AFR)	0.21	0.20	0.27	0.34	0.41	0.48
China (CHN)	0.72	0.83	0.74	0.66	0.57	0.48
India (IDI)	0.22	0.23	0.29	0.36	0.42	0.48
Latin America and Caribbean (LAM)	0.58	0.60	0.57	0.54	0.51	0.48
Middle East and North Africa (MEA)	0.55	0.52	0.51	0.50	0.49	0.48
North America (NAM)	5.23	5.66	4.36	3.07	1.78	0.48
Pacific OECD (PAO)	2.87	3.26	2.56	1.87	1.18	0.48
Other Pacific Asia (PAS)	0.68	0.73	0.67	0.60	0.54	0.48
Reforming Economic Countries (REC)	1.83	2.10	1.70	1.29	0.89	0.48
Western Europe (WEU)	2.75	3.15	2.48	1.82	1.15	0.48
WORLD	1.07	1.11	0.91	0.75	0.60	0.48

B. Abatement Policies

In our simulations (see section 4 below) we distinguish between two abatement regimes which capture the extreme points of non-cooperative and cooperative carbon abatement policy:

NTR: The carbon limits *CARBLIM* strictly apply at the country level. In other words, countries are not allowed to buy or sell emission permits on international markets. All emission reductions must take place domestically.

TRD: Emission rights can be traded across borders. There are no restrictions to the eligibility of trading partners and the magnitude of emission trade.

Throughout the simulations we treat emission limitations as a resource constraint. We then can interpret the shadow price on the emission constraint, i.e. the marginal abatement costs, as the carbon tax rate or likewise the price of the non-tradable / tradable emission rights. In the *TRD* case there will be an equalization of marginal abatement costs across countries. Revenues from carbon taxes or permits enter the national accounts in each region.

3. Model Characteristics and Parameterization

A. Model Characteristics

The model features 10 regions (countries) which are linked through bilateral trade flows. The economic structure of each region consists of 4 production sectors (1 non-energy macro good sector and 3 fossil fuel sectors) whose outputs are demanded by intermediate production, exports, investment and a representative consumer. Table 2 gives an overview of the regional and sectoral aggregation.

Table 2: Overview of sectors and regions

Sectors		Regions	
Energy		AFR	Sub-Saharan Africa
COA	Coal	CHN	China
GAS	Natural gas	IDI	India
OIL	Crude oil	LAM	Latin America and the Caribbean
Non-Energy		MEA	Middle East and North Africa
ROI	Non-energy macro good aggregate	NAM	North America (USA and Canada)
		PAO	Pacific OECD (Japan, Australia, New Zealand)
		PAS	Other Pacific Asia
		REC	Reforming economy countries (newly independent states of the former Soviet Union, Central and Eastern Europe)
		WEU	Western Europe

This section provides a non-technical description of the intertemporal multi-sector, multi-region model underlying our analysis. The detailed algebraic model formulation can be downloaded from ftp://ftp.zew.de/pub/zew-docs/div/c&c.pdf.[3]

Producers and representative consumers behave according to the competitive paradigm, in the sense that they take market prices as given. Consumption and investment decisions are based on rational point expectations of future prices. The representative agent for each region maximizes lifetime utility from consumption which implicitly determines the level of savings. Entrepreneurs choose investment in order to maximize the present value of their firms. Rational expectations in a deterministic model confer clairvoyance on all producers and consumers. While this assumption is strong, it seems to be the only consistent approach in a deterministic model (see e.g. Manne and Richels 1992).

[3] A disk including all the data and the programs for the replication of our results can be obtained from the authors on request.

In each region production of the non-energy macro good is captured by an aggregate production function which characterizes technology through transformation possibilities on the output side (between production for domestic and export markets) and substitution possibilities on the input side (between alternative combinations of inputs). On the output side production is split between goods produced for the domestic markets and goods produced for the export market subject to a constant elasticity of transformation. On the input side capital, labor and an energy aggregate of fossil fuels trade off with a constant elasticity of substitution (CES). Production of the energy aggregate is described by a CES function which reflects substitution possibilities for different fossil fuels (i.e., coal, gas, and oil). Fossil fuels are produced from fuel-specific resources and the non-energy macro good subject to a CES technology. The elasticities of substitution between the resource inputs and non-energy inputs are calibrated to specified supply elasticities for each of the fossil fuels. The resource supplies are calibrated to baseline estimates of fossil fuel production by IIASA/WEC (IIASA 1998).

The representative household in each region chooses to allocate lifetime income across consumption in different time periods in order to maximize lifetime utility. In each period households face the choice between current consumption and future consumption, which can be purchased via savings. That is, consumption and the level of savings are endogenously determined in each period by intertemporal utility maximization. The trade-off between current consumption and savings is given by a constant intertemporal elasticity of substitution. Households demand an aggregate consumption good, which is a CES composite of the non-energy macro good and a household-specific energy aggregate.

Output is divided between consumption (incl. exports and intermediate demand) and investment, and investment augments the (depreciated) capital stock in the next period. Investment takes place as long as the marginal return on investment equals the marginal cost of capital formation. The rates of return are determined by a uniform and endogenous world interest rate such that the marginal productivity of a unit of investment and marginal utility of a unit of consumption is equalized within and across countries.

Following Armington (1969), domestic, imported and exported varieties of the non-energy goods are distinguished by origin. The Armington aggregation function provides a constant elasticity of substitution between domestic and imported varieties for the non-energy good for all buyers in the domestic market. With respect to trade in energy, fossil fuels from different regions are treated as perfect substitutes, which implies that we use net trade data with no cross-hauling. International capital flows reflect borrowing and lending at the world interest rate, and are endogenous subject to an intertemporal balance of payments constraint: there is no change in net indebtedness over the entire model horizon.

In each region there are backstop technologies for producing the industrial energy aggregate and the household energy aggregate. The backstop technology defines the price for a carbon free energy source in infinite supply (e.g. photovoltaic, fuel cells) and provides an upper limit on the marginal costs of reducing carbon emissions. In each region, the backstops are produced employing the region's non-energy macro good.

B. Parameterization

Data from two different sources are combined to calibrate parameters of the functional forms from a given set of quantities, prices and elasticities: The GTAP database (McDougall et al. 1997) which includes detailed input-output bales for 45 regions and 50 sectors as well as a world trade matrix with bilateral trade flows for all sectors and regions; and the IEA energy statistics (IEA 1996) that provide physical energy flows and energy prices for industrial and household demands. Reconciliation of these data sources (Rutherford and Paltsev 2000) involves replacement of GTAP's aggregate input-output monetary values for energy supply and demand with physical energy flows and energy prices as given in IEA's energy statistics. The major advantage is that implicit marginal abatement cost curves for carbon emissions and hence the cost evaluation of carbon emission constraints are based on real energy flows rather than aggregate monetary data, which strengthens the credibility of the quantitative results.

For the baseline calibration of our multi-region dynamic CGE model we incorporate IIASA/WEC projections on the future development of GDP and fossil fuel production for the 21st century differentiated by countries (IIASA 1998). The exogenous assumptions on fossil fuel production for our business-as-usual (*BAU*) scenario imply a reference emission level for the world as a whole. At the country level, the *BAU* emission trajectory determines the extent to which potential reduction obligations with respect to a reference year (in our case: 1990) bind in the future.

Population projections as given by the World Population Prospects (UN 1996) determine the carbon budget trajectory *CARBLIM* for each region according to our permit allocation formula (given a 25 % cutback of global carbon emissions in 2050 as compared to 1990 world emission levels).

4. Results

A. Emissions and Marginal Abatement Costs

Figures 1 and 2 depict the carbon trajectories under *BAU*, *NTR* and *TRD* together with the mandated time-path of emission rights *CARBLIM* which is derived from our C&C-formula. Under *BAU*, global emissions increase from roughly 6 Gt. carbon in 2000 to roughly 11.5 Gut carbon in 2050 (see Figure 1). This *BAU* trajectory is in line with the IIASA/WEC scenario A1 (IIASA 1998). By 2050 the administered global carbon limit of 4.4 Gut under C&C is more than 60 % below *BAU* emissions which indicates the need for substantial adjustment towards less carbon-intensive production and consumption patterns. At the global level, strictly domestic abatement action (*NTR*) involves less carbon emissions than free trade in permit rights (*TRD*). The reason is that regions IDI, AFR, and MEA do not face a binding carbon constraint under *NTR*, i.e. they do not use their emission rights to the full extent.[4]

When emission rights get internationally tradable, IDI, MEA, and AFR sell abundant emission rights which leads to an effective increase in global carbon emissions of roughly 10% by 2050 as compared to the *NTR* case. This phenomenon has been referred to as *hot air* in the context of the Kyoto Protocol (see e.g. Böhringer 2000). In principle, the occurrence of *hot air* warrants some caution with respect to welfare analysis. In order to undertake consistent comparison across alternative abatement scenarios we either need to specify gross benefits from abatement or hold the global abatement constant. Both approaches have larger problems on their own. The quantification of benefits from climate change across regions is highly uncertain, which, in fact, motivated our choice of a cost-effectiveness framework for our analysis from the very beginning. Assuring exactly the same global carbon emission profile across the *NTR* and *TRD* scenario requires the definition of some adjustment rules for carbon entitlements under the *TRD* case. In view of the arbitrariness of such an adjustment rule and its potentially low degree of political feasibility we decided to include hot air in our central policy simulations. After all, the amount of hot air is rather small over the whole time horizon (see world emission profiles for *TRD* and *NTR* in Figure 1).[5]

The magnitude of the marginal abatement cost in the *NTR* case depends crucially on the extent to which the carbon emission constraint binds the respective economies. The effective reduction requirement for the different regions at any point over time is given by the

[4] As Figures 2g, 2h and 2j show, these regions nevertheless have a substantial increase of emissions under *NTR*.

[5] We have performed sensitivity analysis with respect to the suppression of hot air; the quantitative results change only slightly, and all our qualitative findings remain robust (see download ftp://ftp.zew.de/pub/zew-docs/div/c&c.pdf for the concrete results).

distance between *BAU* and *CARBLIM*. The higher the effective cut-back, the higher are – ceteris paribus – the carbon taxes necessary to meet the emission constraint.

Figures 3 and 4 show the carbon tax trajectories for the *NTR* case. In addition we have plotted the price trajectory of tradable permits (*WORLD*) as a reference line to explain the pattern of permit trade emerging from the countries' before trade situation.

Comparing regional tax rates in the *NTR* case, which range from 0 up to 1600 $US (in the final period 2050), there is considerable potential for international emissions trading, i.e. global equalization of marginal abatement costs.

There are no carbon taxes under *NTR* for regions IDI, AFR, and MEA. This is simply because C&C does not bind economic growth in these regions. In all other countries, C&C constrains economic development more and more over time inducing a continuous increase in marginal abatement costs. In other words, as cheap mitigation options are exhausted over time it gets more and more costly at the margin to substitute away from carbon.

OECD regions (NAM, WEU, PAO) and REC face relatively high effective abatement requirements under the C&C proposal and therefore need relatively high carbon taxes to reduce their carbon use from *BAU* levels to the permissible *CARBLIM*. For developing regions LAM, CHN, and PAS, the C&C-proposal imposes less stringent abatement requirements which translates into relatively lower carbon tax rates.

Countries whose marginal abatement costs under *NTR* are below the global carbon tax (WORLD) will sell permits and abate more emissions. In turn, countries whose marginal abatement costs are above the global tax rate will buy permits and abate less emissions.

Figures 2, 3 and 4 indicate that NAM, WEU, PAO, and REC buy emission rights whereas IDI[6], AFR, MEA, CHN, LAM, and PAS sell emission rights.

Emissions trading implies that the group of permit buyers reduce their emissions between 2010 and 2050 by only 70 % of what they would have to in the *NTR* case. CHN, LAM, and PAS abate about 1.3 times as much as they would under *NTR*. IDI, AFR, and MEA do not undertake any abatement in the *NTR* case; under the *TRD* regime they do abate more than 25 percent of their aggregate *BAU* emissions between 2010 and 2050.

[6] In an intertemporal perspective, IDI is a large net seller of emission rights although it buys carbon rights under *TRD* at the very beginning of C&C. The increase in lifetime income due to carbon trade is used in part for an increase in consumption during the initial period. The induced increase in production requires additional purchases of carbon rights – otherwise domestic production would be constrained by the small initial emission budget of C&C.

Figure 1: Global carbon emission trajectories

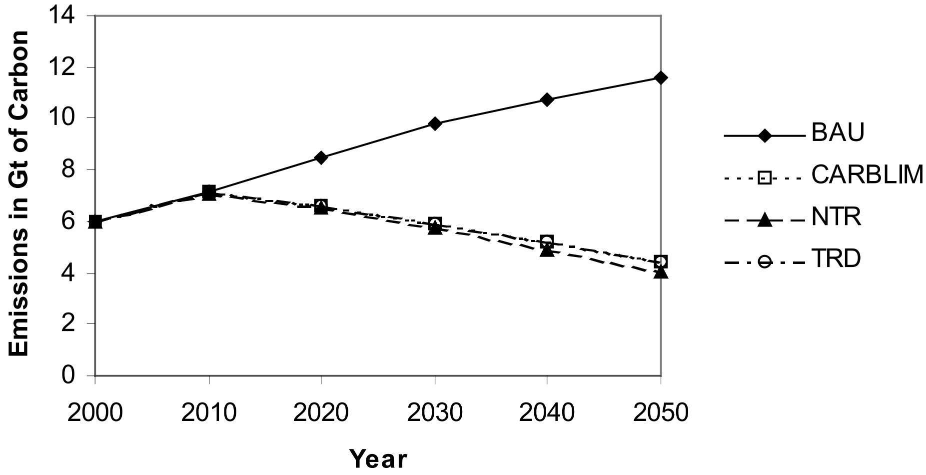


Figure 2: Emission profiles at country level under C&C

Key: BAU CARBLIM NTR TRD

Fig. 2a: Emissions in country AFR

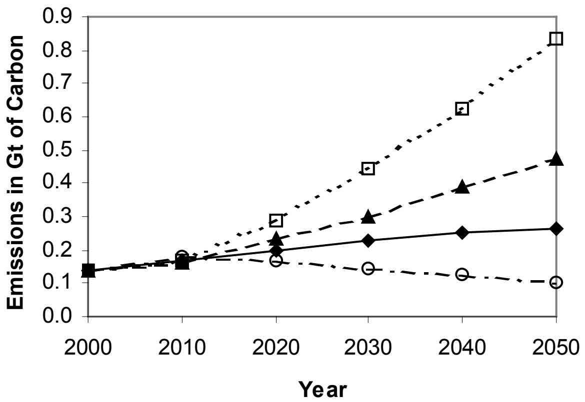


Fig. 2b: Emissions in country CHN

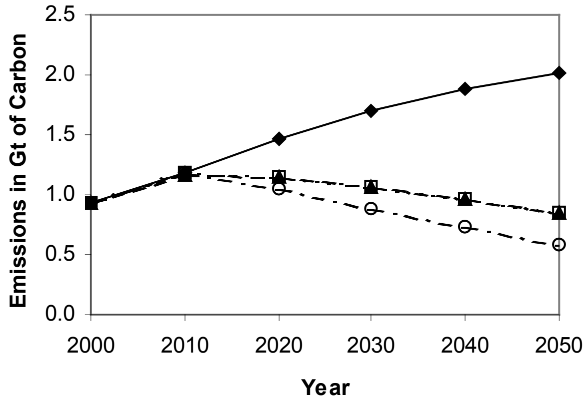


Fig. 2c: Emissions in country IDI

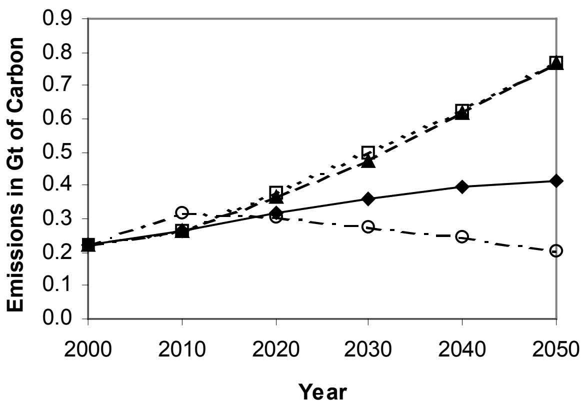


Fig. 2d: Emissions in country LAM

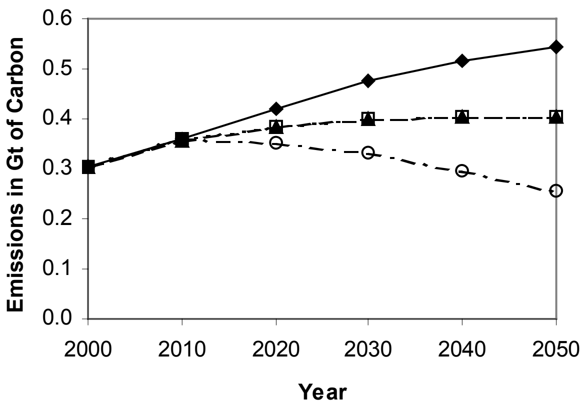


Figure 2 (continued): Emission profiles at country level under C&C

Key: BAU CARBLIM NTR TRD

Fig. 2e: Emissions in country MEA

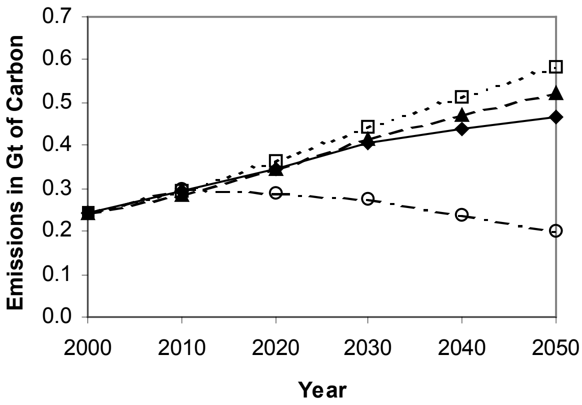


Fig. 2f: Emissions in country NAM

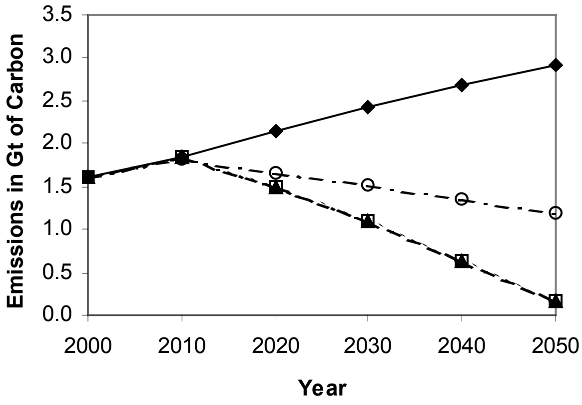


Fig. 2g: Emissions in country PAO

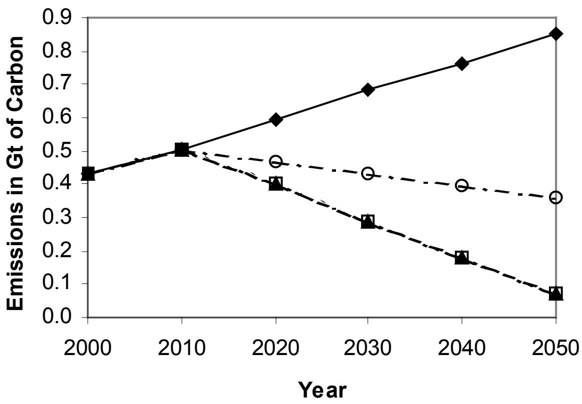


Fig. 2h: Emissions in country PAS

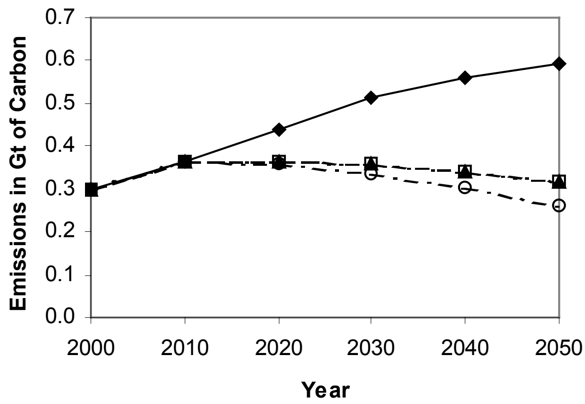


Fig. 2i: Emissions in country REC

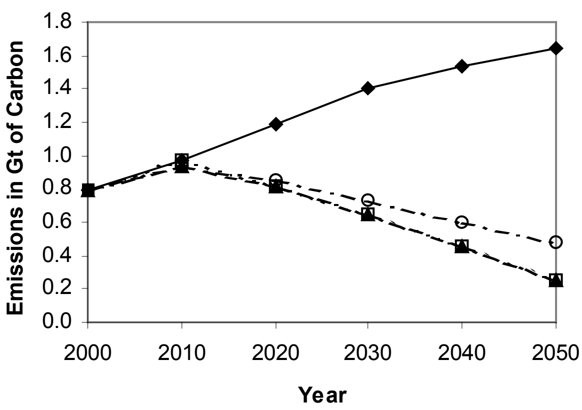


Fig. 2j: Emissions in country WEU

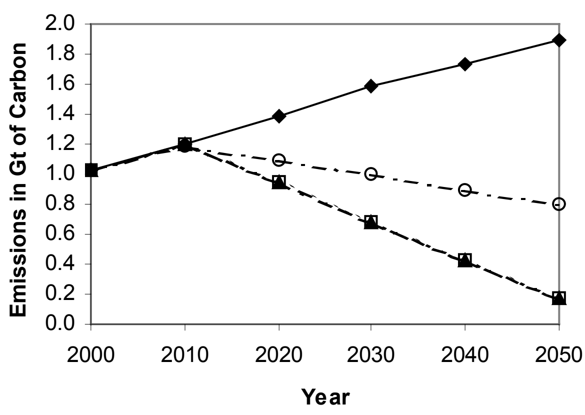


Figure 3: Carbon taxes under *NTR* below global *TRD* permit price (WORLD) for C&C

N.B.: IDI, MEA and AFR without any carbon taxes

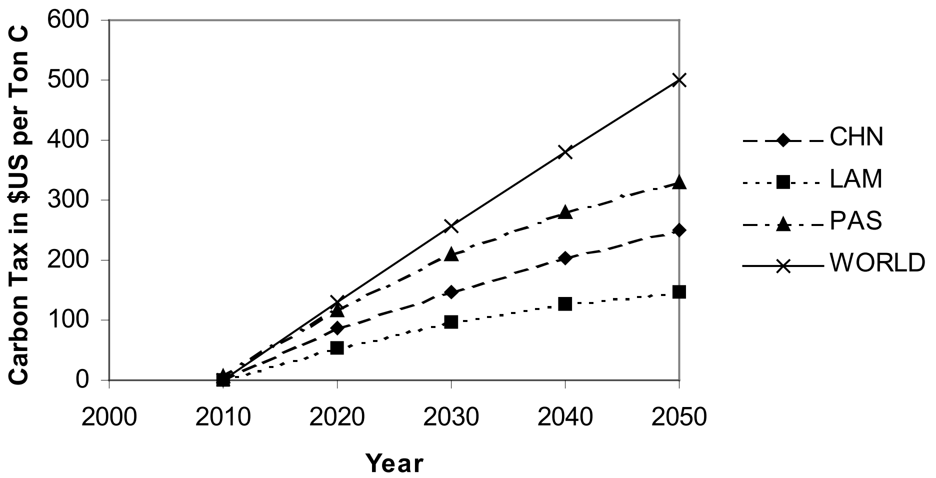
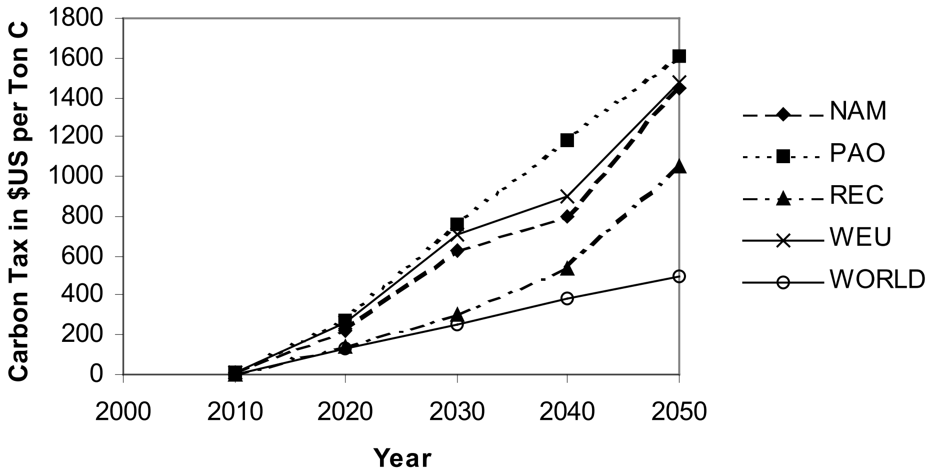


Figure 4: Carbon taxes under *NTR* above global *TRD* permit price (WORLD) for C&C



B. Welfare Effects

We measure welfare changes by the Hicksian equivalent variation (HEV) in lifetime income discounted to the year 2000. The welfare changes that arise from carbon abatement under C&C are reported in Table 3 for the *NTR* and *TRD* case.

We start interpretation of our results for the *NTR* case. A major determinant of a country's adjustment costs to emission constraints is its baseline economic development. The *BAU* scenario determines baseline emission growth which in turn implies the effective cut-back requirement with respect to an exogenous emission target profile (in our case: *CARBLIM*). Larger required reduction in carbon emissions as a percentage of baseline emissions leads to higher abatement costs.

Table 3: HEV in lifetime income (% change from *BAU*) under C&C – *NTR* versus *TRD*

	NTR	*TRD*
AFR	-1.74	14.24
CHN	-2.35	-0.74
IDI	0.16	15.15
LAM	-0.9	0.3
MEA	-2.6	2.03
NAM	-2.64	-2.16
PAO	-1.17	-0.96
PAS	-0.04	0.17
REC	-7.82	-6.97
WEU	-1.34	-1.1
WORLD	-1.82	-0.75

However, emission abatement in large open economies will not only affect the allocation of domestic resources but also change international market prices. The change in international prices implies an indirect *secondary* burden or benefit for *all* countries trading internationally which can significantly alter the *primary* economic implications of the domestic abatement policy. Depending on its trade patterns a region will gain or lose from these international spillovers, i. e. changes in its terms of trade. With respect to carbon abatement and our sectoral disaggregation, it is useful to distinguish spillovers from two major international markets:

- *fossil fuel markets:* A larger cutback in global fossil fuel consumption depresses the international prices of fossil fuel (the magnitude of depression depends to a large extent on the underlying supply elasticities). In this respect a region which imports fossil fuels will benefit from the contraction of world fuel consumption whereas a country which exports fossil fuels will suffer.[7]
- *non-energy markets:* Due to product heterogeneity associated with the Armington assumption for non-energy macro good trade, countries are able to pass on an increase in production costs to other countries. Whether a country will experience a terms-of-trade loss or gain on the macro good markets depends on its initial trade shares and elasticities (of export supply and import demand) as well as differences in the cost changes of producing the macro good induced by the abatement scenario. The price differentials for

[7] If a region at the same time is a net exporter of some fuel and a net importer of some other fuel the aggregate fossil fuel market effect is ambiguous.

Armington goods of the same variety across regions determine the substitution effects in international trade, that is whether a country will rather lose or win export markets.

While at the global level terms of trade effects should net out to zero it is clear that at the single country level the welfare implications will have opposite directions.[8] The welfare implications for IDI, MEA, and AFR under *NTR* explicitly reveal the importance of international spillovers. Though these regions do not have to undertake domestic abatement, they nevertheless are affected by abatement action in other countries through international markets, i. e. changes in international prices (the terms of trade).[9] While IDI slightly gains from international spillovers, MEA and AFR suffer from abatement elsewhere. To analyze the gross welfare implications associated with carbon emission constraints in open economies in more detail, we employ a decomposition method as described in Böhringer and Rutherford for a static application (Böhringer and Rutherford 2002). This decomposition allows for a natural break down of the aggregate economic effect into a domestic policy effect (i. e., domestic adjustment holding international prices constant at the *BAU* level) and international spillovers (the residual effect accounting for changes in the terms of trade). Table 4 summarizes the outcome of the decomposition for the *NTR* case.

Table 4: Decomposition of HEV in lifetime income under *NTR* (in % from *BAU*) for C&C

	A	B	C	D
AFR	0.00	-1.28	-1.74	-1.74
CHN	-1.49	-1.20	-0.86	-2.35
IDI	0.00	1.29	0.16	0.16
LAM	-0.03	-0.51	-0.87	-0.90
MEA	0.00	-2.77	-2.60	-2.60
NAM	-2.56	-0.08	-0.08	-2.64
PAO	-1.20	0.03	0.03	-1.17
PAS	-0.25	0.29	0.21	-0.04
REC	-7.38	-0.67	-0.43	-7.82
WEU	-1.41	0.11	0.07	-1.34

A: Domestic policy effect of abatement keeping international prices at the *BAU* level

B: Fossil Fuel Price Effect: Welfare effect when we account for changes in international fuel prices but keep the price of the macro good at the *BAU* level

C: Isolated terms of trade effect (D - A)

D: Full carbon abatement effect (A + C) – see column *NTR* of Table 4

[8] The gains for one country imply losses for other countries.

[9] *Terms of trade* can be used to determine whether a country will benefit or lose from the change in international prices. Terms of trade are measured as the ratio of a country's imports to its exports. A positive change in the terms of trade then means that the country has to export less for a given amount of imports, i.e. the country experiences a welfare gain from the change in international prices.

The domestic policy effect (column A of Table 4) reports the welfare impacts of carbon constraints assuming that international prices are unaffected from the domestic (tax) abatement policy. By definition, the domestic policy effect is zero for regions IDI, AFR and MEA which do not have to undertake any carbon abatement. As expected, the domestic policy impact is negative for those countries that actually undertake emission abatement. Binding emission limits require a reduction in fossil fuel consumption, which causes domestic industries to substitute towards less emission-intensive, more costly manufacturing and production techniques. In addition, fuel for final consumption becomes more expensive. The increase of the real consumption price index implies a loss in real income (welfare) for households. The magnitude of the inframarginal welfare loss associated with the domestic abatement policy depends on a number of factors such as the effective reduction requirement with respect to the baseline and the initial energy (emission) intensities. Column A of Table 4 joint with Figure 4 indicate that the ordering of inframarginal abatement costs may get reversed as compared to the ranking in marginal costs due to differences in energy intensities. For example, REC and PAO face almost the same (relative) effective reduction requirement but whereas REC has high inframarginal costs joint with low marginal costs the reverse holds for PAO. This result reflects the large differences in *BAU* (fossil) energy intensities which is high for REC and low for PAO.

As outlined above an important determinant for the sign and magnitude of the aggregate terms-of-trade effects are changes in international fossil fuel prices together with the region's initial fossil fuel trade position. The welfare implications of spillovers from international fossil fuel markets at the single region level are reported in column B of Table 4. We see that IDI, WEU, PAO, and PAS experience welfare gains from changes in international fuel prices whereas CHN, MEA, NAM, REC, LAM, and AFR face welfare losses. Not surprisingly, MEA as the major exporter of oil suffers most from the fall in fossil fuel prices.[10] CHN (an important future coal exporter) and REC (a supplier of large gas quantities to world markets) are also affected negatively from the price decrease on international fossil fuel markets.

Column C of Table 4 reports the welfare implications of total terms-of-trade changes across regions. Jointly with column B we see that price changes on the international markets for the non-energy macro good impose major welfare losses for regions IDI, AFR, and LAM whereas CHN, MEA, and REC can partially offset the negative welfare impacts due to the fall in fuel prices. Macro good trade relations with high carbon tax countries (i.e. NAM, PAO or

[10] Likewise oil exporting AFR and LAM face a substantial decline in export revenues from oil sales.

WEU) make IDI, AFR, and LAM to net tax burden importers rather than net tax burden exporters. The opposite applies for regions CHN, MEA, and REC.

Turning to the *TRD* case, Table 3 indicates that international emissions trading under C&C not only reduces the global welfare loss by half, but is *universally* beneficial as compared to the *NTR* case. Although we know that - in the absence of second-best effects - emissions trading must improve *global* efficiency[11], there is no guarantee - a priori - that trading provides a *Pareto* improvement over a no-trade regime, i.e., that *every* region will benefit from trading. The reason behind this ambiguity are terms-of-trade effects which - contrary to the wide-spread partial equilibrium approach in environmental policy analysis - are taken into account in our general equilibrium framework. In first place (i. e. without induced changes in international prices) all countries will benefit from carbon trade. However, secondary terms-of-trade effects could offset (or enhance) the primary benefit from trading carbon across domestic borders. Obviously, the prospects that the unambiguous primary gains from emissions trading dominate the ambiguous secondary terms-of-trade effects depend on the initial permit allocation. The more countries deviate in marginal abatement costs for the *NTR* case, the higher are the global efficiency gains and - ceteris paribus - the associated gains at the country level. Under C&C which entails large cross-country differences in marginal abatement costs the primary efficiency gains from emissions trading are high enough to more than outweigh potentially negative terms-of-trade effects for all countries.

Most outstanding are the substantial gains from trade in carbon rights for regions IDI, AFR, and MEA. They improve their economic welfare considerably even *beyond BAU* levels. Note that these are the regions which do not exploit their carbon budget to the full extent under *NTR.* Their (shadow) price of emission rights increases dramatically from zero in the *NTR* case to the world market permit price under *TRD*. To put it differently: Their abundant emission rights under *NTR* become a valuable international resource which provides them with substantial additional net income. Developing regions LAM and PAS also do slightly better under the *TRD* case of C&C as compared to *BAU*. For OECD regions (NAM, WEU, and PAO), the reforming economy countries (REC)[12], and China (CHN) international emissions trading reduces adjustment costs but still leaves them with significant welfare losses as compared to a global doing-nothing case (business as usual). Table 5 provides insights into the magnitude of emissions trading at the regional level.

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[11] In our concrete case, global abatement costs drop more than by a half for *TRD* as compared to the *NTR* regime.

[12] Relatively worst affected from C&C under both *NTR and TRD* are the reforming economic countries (REC). We can see from column A of Table 4 that the main reason for the welfare losses is the costly adjustment of highly energy-intensive production and consumption towards a significantly less emission-intensive economic structure.

Table 5: Value of carbon emission rights exports in billion $\$US_{2000}$

	2020	2030	2040	2050
AFR	16	77	190	366
CHN	13	48	90	134
IDI	9	56	146	281
LAM	4	18	41	74
MEA	10	43	105	191
NAM	-21	-108	-271	-509
PAO	-9	-37	-82	-144
PAS	1	5	14	29
REC	-4	-21	-53	-111
WEU	-20	-82	-179	-310

In accordance with our inframarginal welfare results, we see that emissions trading implies substantial financial flows from developed countries to the developing world. The biggest payers are NAM and WEU; their payments by 2050 amount to 509 and 310 billion US$. To put these figures in perspective, note that they represent 2.5% and 1.4%, respectively, of these regions' gross domestic product. The corresponding percentages for the year 2030 are 0.7% and 0.5%. These flows do not appear excessive in relation to the gross domestic product. In fact they are of a comparable order of magnitude as current conventional development aid.

C. Sensitivity Analysis

We have performed a detailed sensitivity analysis with respect to changes in four key assumptions: oil price responsiveness, energy demand responsiveness, backstop costs, and the ease of substitution among traded non-energy goods (non-energy trade impacts). Details of these calculations are provided in the download. We find that all our qualitative insights robust: C&C under *TRD* provides a Pareto-improvement over the *NTR* case where most developing countries are better off than under *BAU*.

Oil Price Responsiveness

As has been illustrated in section 4B, the price drop on the world's crude oil market due to reduced demand is an important determinant of the welfare implications from global carbon abatement at the country level. The supply elasticity for crude oil determines how its price responds to changes in the demand for crude oil. The lower the supply elasticity, the more responsive is the price of oil to a change in the demand for oil. For a given reduction in global crude oil demand, the price drops more for lower elasticity values than for higher values. Increasing the price response (decreasing the supply elasticity), thus, causes oil exporting nations to suffer more when a carbon abatement policy is enacted. Conversely, higher price responses (lower supply elasticities) lead to greater benefits for oil importing countries.

Energy Demand Responsiveness

The adjustment costs of emission constraints depend on the ease of substitution between energy and other factors in production and consumption. The end-use demand elasticity determines how total energy demand responds to increases in the price of energy in both the short- and long-runs. In the model parameterization, the substitution elasticity between energy and other factors - and hence the implicit energy demand elasticity - rises linearly over time between a lower short-run value and a higher long-run value to reflect empirical evidence on differences between short-run and long-run adjustment costs. In the sensitivity analysis, we alter the short-run value. As expected total welfare costs induced by emission constraints decline towards higher energy demand responsiveness because it gets cheaper to substitute away from carbon-intensive energy carriers in production and consumption. At the country level the potential decrease in direct adjustment costs may be offset by a deterioration in the terms of trade.

Backstop Costs

In addition to the fossil fuels oil, coal and gas, the model includes a carbon-free fuel that can substitute perfectly for any of the fossil fuels. This fuel is referred to as a backstop fuel of which each region is assumed to have an inexhaustible supply. Since this energy source is unavailable today, though it is believed to be available in the future, its price is assumed to be more expensive than the current fossil energy aggregate. As we move from lower to higher backstop costs, the decrease in global compliance costs under *NTR* confirms economic intuition that less expensive carbon free backstop fuel makes worldwide adjustment cheaper. Interestingly, global compliance costs slightly decrease for the case of global emissions trading when we move from our central (middle) value of backstop costs to a higher value. The reason are larger income effects under emissions trading towards higher backstop costs: The latter imply higher domestic abatement costs for industrialized countries - the world carbon price under trading increases which implies higher income to various developing countries from emission sales. With decreasing marginal utility of income this produces (slightly) lower global welfare losses as compared to the central case.

Non-Energy Trade Impacts

Opposite to fossil fuel goods, the imported and domestically produced non-energy macro goods are treated as imperfect substitutes. The substitution possibility between the domestically produced good and the import aggregate from other regions is characterized by a constant (Armington) elasticity of substitution. The same applies to imports from different regions within the import aggregate. These trade elasticities together with the respective bilateral trade shares are key determinants for the terms-of-trade effects on the non-energy market. If income effects are of secondary order which is the case for the *NTR* scenario, world-wide cost of carbon abatement move inversely with trade elasticities because - when domestic and imported goods are closer substitutes - countries can more easily substitute away from carbon-intensive inputs into production and consumption. However, under emissions trading the welfare gain from improved substitution may be offset from adverse income effects for the developing regions (see transition from the central value towards the higher value).

5. Summary and Policy Implications

In this paper we have used a dynamic multi-region general equilibrium model of the world economy to assess the economics of a scenario which entails *contraction* of global carbon emissions by 25 % as compared to 1990 emission levels cum *convergence* towards equal per capita emission rights over the time horizon 2010 through 2050. The C&C scenario reflects both, scientific evidence on the need for stringent future emissions reduction at the global level and broadly accepted equity considerations based on the justice principle of "equality of resources".

It appears that the "Contraction and Convergence" paradigm (C&C), merged with the idea of international emissions trading, has potential merits in terms of cost effectiveness and distributive equity (and hence international political feasibility). Emissions trading not only reduces global welfare costs by one half, but also delivers a Pareto improvement over *NTR*. In view of induced changes in the terms of trade and ensuing income effects, this is not a trivial result. Most developing regions are even better off than under *BAU*. Conversely, in the absence of emissions trading, several of the least developed countries may lose even though the emission limits implied by C&C do not bind these economies due to low *BAU* growth.

The purpose of this paper has been mainly a positive one, namely to examine the quantitative implications of a stylized framework for international greenhouse gas abatement in a long-term perspective. From a methodological point of view, a major insight from our results is that changes in the terms of trade play an important role in shaping the economic implications of global carbon abatement policies and should therefore not be neglected in such an analysis.

References

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

Beckerman, W. and J. Pasek (1995), The equitable international allocation of tradable carbon emission permits, Global Environmental Change 5 (5), 404-413.

Bertram, G. (1992), Tradable emission permits and the control of greenhouse gases, *Journal of Development Studies 28* (3), 423-446.

Böhringer, C. (2000), Cooling Down Hot Air - A Global CGE Analysis of Post-Kyoto Carbon Abatement Strategies, *Energy Policy,* 28, 779-789.

Böhringer, C. and T. F. Rutherford (2002), Carbon Abatement and International Spillovers – A Decomposition of General Equilibrium Effects, *Environmental and Resource Economics,* 22*,* 319-417.

Bohm, P. and B. Larsen (1994), Fairness in a Tradable Permit Treaty for Carbon Emissions Reductions in Europe and the former Soviet Union, *Environmental and Resource Economics,* 4, 219-239.

Grubb, M. and J. Sebenius (1992), Participation, Allocation, and Adaptability in International Tradable Emission Permits Systems for Greenhouse Gas Control, in: OECD (ed.), Climate Change: Designing a Tradable Permit System, Paris.

Houghton, J.J. et al. (1996), Climate Change 1995 – The Science of Climate Change, Cambridge University Press.

IEA (1996), International Energy Agency, Energy Prices and Taxes / Energy Balances of OECD and Non-OECD Countries*,* Paris: IEA publications.

IIASA (1998), IIASA/WEC Global Energy Perspectives, http://www.iiasa.ac.at

Kverndokk (1995), Tradable CO_2 emission permits: Initial distribution as a justice problem, *Environmental Values 4*, 129-148.

Lindbeck, A. (1983), The Recent Slowdown of Productivity Growth, *Economic Journal*, 1983.

McDougall, R.A. et al. (1997), The GTAP 4 Data Base, Center for Global Trade Analysis, Purdue University.

Manne, A.S. and R.G., Richels, (1992), Buying Greenhouse Insurance: The Economic Costs of CO2 Emission Limits, Cambridge, MIT Press.

Morrisette, P. and A. Plantinga (1991), The Global Warming Issue: Viewpoints of Different Countries, *Resources* 103, 2-6.

Rose, A. et al. (1998), International equity and differentiation in global warming policy, *Environmental and Resource Economics 12,* 25-51.

Rutherford, T.F. and S.V. Paltsev (2000), GTAP-Energy in GAMS, University of Colorado, Working Paper 00-2, http://debreu.colorado.edu/download/gtap-eg.html.

Shue, H. (1993), Subsistence Emissions and Luxury Emissions, *Law and Policy* 15, 39-59.

UNFCC (1992), United Nations Framework Convention on Climate Change, New York, 9 May 1992, in force 21 March 1994. 31 ILM 849.

UN (1996), United Nations, *World Population Prospects: The 1996 Revision*, New York.

Welsch, H. (1993), A CO_2 Agreement Proposal with Flexible Quotas, *Energy Policy* 21, 748-756.

Contraction and Convergence of Carbon Emissions

An Inter-Temporal Multi-Region CGE Analysis

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Downloadable Appendix

(ftp://ftp.zew.de/pub/zew-docs/div/c&c.pdf)

Appendix A: Algebraic Model Description

This section provides an algebraic summary of equilibrium conditions of our intertemporal multi-region, multi-sector general equilibrium model designed to investigate the economic implications of carbon abatement strategies for the world economy. The following key assumptions apply for the "generic" model (see also Böhringer and Rutherford 2001):

- Output and factor prices are fully flexible and markets are perfectly competitive.
- Labor force productivity increases at an exogenous growth rate (Harrod-neutral technological progress).
- In equilibrium there is a period-by-period balance between exports from each region and global demand for those goods. The model adopts the Armington assumption for export and import markets of a non-energy macro good to differentiate between commodities produced for the domestic market, the export market and the import market (Armington 1969). Fossil fuels are treated as perfect substitutes on international markets.
- In each region, a representative consumer (likewise the social planner) maximizes the present value of lifetime utility subject to (i) an intertemporal balance of payments constraint, (ii) the constraint that the output per period is either consumed (incl. intermediate demand and exports) or invested, and (iii) the equation of motion for the capital stock, i.e. capital stocks evolve through depreciation and new investment. This renders the optimal level of consumption and investment over time.
- The agents have an infinite horizon, and their expectations are forward looking and rational. To approximate an infinite horizon model with a finite horizon model we assume that the representative consumer purchases capital in the model's post-horizon period at a price which is consistent with steady-state equilibrium growth (terminal condition).

The model is formulated as a system of nonlinear inequalities using GAMS/MPSGE (Rutherford 1999) and solved using PATH (Dirkse and Ferris 1995). The inequalities correspond to the three classes of conditions associated with a general equilibrium: (i) exhaustion of product (zero-profit) conditions for constant returns to scale producers, (ii) market clearance for all goods and factors, and (iii) income balance for the representative consumers in each region. The fundamental unknowns of the system are three vectors: activity levels (production indices), non-negative prices, and consumer incomes. In equilibrium, each of these variables is linked to one inequality condition: an activity level to an exhaustion of product constraint, a commodity price to a market clearance condition, and a consumer income variable to an income definition equation. An equilibrium allocation determines production, prices and incomes.

In the following algebraic exposition, the notation Π^X is used to denote the zero-profit function of activity *X*. Formally, all production activities exhibit constant returns to scale, hence differentiating Π^X with respect to input and output prices provides compensated demand and supply coefficients, which appear subsequently in the market-clearance conditions. All prices are expressed as present values.

Exhaustion of Product Conditions

Macro Good Production

Aggregate output in region *r* describes the supply of the non-energy macro good to the domestic market and export market. A separable nested constant elasticity of substitution (CES) cost function is employed to specify the substitution possibilities between capital (*K*), labor (*L*) and an energy composite (*E*). At the top level, a constant elasticity describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. At the second level capital and labor trade off with a unitary elasticity of substitution. On the output side, production is split between goods produced for the domestic market and goods produced for the export market according to a constant elasticity of transformation. The (intra-period) zero-profit condition for the production of the macro good is:

$$\prod\nolimits_{rt}^{Y} = (\theta_r^X \, p_{rt}^{X^{1+\eta_r}} + (1-\theta_r^X) p_{rt}^{1+\eta_r})^{\frac{1}{1+\eta_r}} - \left[\theta_r^{EY} (\frac{p_{rt}^{EY}}{\beta_{rt}})^{1-\sigma_r^{KLE}} + (1-\theta_r^{EY}) \left(w_{rt}^{\alpha_r} v_{rt}^{1-\alpha_r} \right)^{1-\sigma_r^{KLE}} \right]^{\frac{1}{1-\sigma_r^{KLE}}} = 0$$

where:

p_{rt}^X output price of macro good produced in region *r* and period *t* for export market,

p_{rt} output price of macro good produced in region *r* and period *t* for domestic market,

p_{rt}^{EY} price of industrial energy aggregate for macro good production in region *r* and period *t,*

w_{rt} wage rate in region *r* and period *t,*

v_{rt} rental price of capital services in region *r* and period *t,*

θ_r^X benchmark share of exports in macro good production of region *r,*

θ_r^{EY} benchmark share of industrial energy aggregate in macro good production of region *r,*

α_r benchmark share of labor in value-added of macro good production in region *r*,

η_r elasticity of transformation between production for the domestic market and production for the export market of region *r*,

σ_r^{KLE} elasticity of substitution between the energy aggregate and value-added in production for region *r,*

β_{rt} exogenous energy efficiency improvement index, which measures changes in technical efficiency for region *r* in period *t*,

and

Y_{rt} associated dual variable which indicates the activity level of macro good production in region *r* and period *t.*

Fossil Fuel Production

The production of fuels requires inputs of domestic supply (macro good) and a fuel-specific factor which can be thought of as a sector-specific resource.[13] The zero-profit condition has the form:

$$\prod_{rt,ff}^{F} = p_t^{ff} - \left[\theta_r^{ff} q_{rt}^{ff^{1-\sigma_r^{ff}}} + (1-\theta_r^{ff}) p_{rt}^{A^{1-\sigma_r^{ff}}} \right]^{\frac{1}{1-\sigma_r^{ff}}} = 0 \qquad ff \in \{COA, OIL, GAS\}$$

where:

p_t^{ff} world market price of fossil fuel *ff* in period *t,*

q_{rt}^{ff} price of fuel-specific resource for production of fossil fuel *ff* in region *r* and period *t,*

p_{rt}^{A} Armington price of macro good in region *r* and period *t,*

θ_r^{ff} benchmark share of fuel-specific resource for fossil fuel production in region *r,*

σ_r^{ff} elasticity of substitution between the fuel-specific resource and non-energy inputs in fossil fuel production of region *r,*

and

$F_{rt,ff}$ associated dual variable which indicates the activity level of fossil fuel production *ff* in region *r* and period *t.*

The value of the elasticity of substitution σ_r^{ff} between non-energy inputs and the fuel-specific resource determines the price elasticity of fossil fuel supply ε_r^{ff} at the reference point, according to the relation:

[13] A constant returns to scale production function with convex levelsets exhibits decreasing returns to scale in *remaining* factors when one or more inputs are in fixed supply. We exploit this result in representing a decreasing returns to scale function through a constant returns to scale activity which uses the fuel-specific factor.

$$\varepsilon_r^{ff} = \sigma_r^{ff} \frac{\theta_r^{ff}}{1-\theta_r^{ff}}.$$

Armington Production

Inputs of the macro good into energy production, investment demand and final consumption are a composite of a domestic and imported variety which trade off with a constant elasticity of substitution. The corresponding zero profit condition for the production of the Armington good is given by:

$$\prod_{rt}^{A} = p_{rt}^{A} - \left[\theta_r^A \, p_{rt}^{1-\sigma_r^A} + (1-\theta_r^A) \left[\left(\sum_s \theta_{sr}^M \, p_{st}^{X^{1-\sigma_r^M}} \right)^{\frac{1}{1-\sigma_r^M}} \right]^{1-\sigma_r^A} \right]^{\frac{1}{1-\sigma_r^A}} = 0$$

where:

θ_r^A benchmark share of domestic macro input into Armington production in region *r,*

θ_{sr}^M benchmark share of imports from region *s* (aliased with index *r*) in total macro good imports of region *r*,

σ_r^A Armington elasticity of substitution between domestic macro good and imported macro good aggregate for region *r*,

σ_r^M elasticity of substitution between macro good imports for region *r,*

and

A_{rt} associated dual variable which indicates the activity level of Armington production in region *r* and period *t.*

Production of the Industrial Energy Aggregate

Energy inputs to the macro production are a nested separable CES aggregation of oil, gas and coal. Gas and oil trade off as relatively close substitutes in the lower nest of the energy composite; at the next level the oil and gas composite combines with coal at a lower rate. The zero-profit condition for the production of the industrial energy aggregate is:

$$\prod_{rt}^{EY} = p_{rt}^{EY} - \{\theta_r^{COA}(p_t^{COA} + pcarb_{rt} CO2_{COA})^{1-\sigma_r^{COA}} + (1-\theta_r^{COA})$$

$$[\theta_r^{OIL}(p_t^{OIL} + pcarb_{rt} CO2_{OIL})^{1-\sigma_r^{LQ}} + (1-\theta_r^{OIL})(p_t^{GAS} + pcarb_{rt} CO2_{GAS})^{1-\sigma_r^{LQ}}]^{\frac{1-\sigma_r^{COA}}{1-\sigma_r^{LQ}}}\}^{\frac{1}{1-\sigma_{COA}}} = 0$$

where:

$pcarb_{rt}$ carbon price in region *r* and period *t*,

$CO2_{ff}$ physical carbon coefficient for fossil fuels,

θ_r^{COA} benchmark share of coal input into industrial energy aggregate of region *r,*

θ_r^{OIL} benchmark share of the oil input into the gas and oil composite of industrial energy production in region *r,*

σ_r^{COA} elasticity of substitution between coal and the gas and oil composite in industrial energy production of region *r,*

σ_r^{LQ} elasticity of substitution between gas and oil in industrial energy production of region *r,*

and

EY_{rt} associated dual variable which indicates the activity level of industrial energy aggregate production in region *r* and period *t.*

Production of the Household Energy Aggregate

Energy demanded by the household is a CES aggregate of fossil fuels. The zero-profit condition for the production of the household energy aggregate has the form:

$$\prod_{rt}^{EC} = p_{rt}^{EC} - \left(\sum_{ff} \theta_{r,ff}^{EC} (p_t^{ff} + pcarb_{rt} CO2_{ff})^{1-\sigma_r^{EC}} \right)^{\frac{1}{1-\sigma_r^{EC}}} = 0$$

where:

p_{rt}^{EC} price of household energy aggregate for region r and period t ,

$\theta_{r,ff}^{EC}$ benchmark share of fossil fuel input *ff* in the household energy aggregate of region *r,*

σ_r^{EC} elasticity of substitution between fossil fuel inputs within the household energy aggregate,

and

EC_{rt} associated dual variable which indicates the activity level of household energy aggregate production in region *r* and period *t.*

Production of the Household Consumption Aggregate

In final consumption demand the household energy aggregate trades off with the macro good at a constant elasticity of substitution:

$$\prod_{rt}^{C} = p_{rt}^{C} - \left(\theta_r^C \, p_{rt}^{A^{1-\sigma_r^C}} + (1-\theta_r^C) \, p_{rt}^{EC^{1-\sigma_r^C}} \right)^{\frac{1}{1-\sigma_r^C}} = 0$$

where:

p_{rt}^{C} price of household consumption aggregate for region r and period *t,*

θ_r^C benchmark share of macro good into aggregate household demand of region *r,*

σ_r^C elasticity of substitution between macro good and energy aggregate in household consumption demand of region *r,*

and

C_{rt} associated dual variable which indicates the activity level of household consumption in region *r* and period *t.*

Backstops for Industry and Household Energy Aggregate

For each region there is a carbon-free backstop for the industrial energy aggregate and the household aggregate. This backstop is available in infinite supply at a price which is calculated to be a multiple of the macro good price. Below, we take explicit account of the non-negativity constraint for backstop production:

$$\prod_{rt}^{\tau} = p_{rt}^{\tau} - a_r^{\tau} p_{rt}^{A} \leq 0 \qquad \tau \in \{BC, BY\}$$

where:

p_{rt}^{τ} price of energy backstop for industry (τ = BY) or household (τ = BC) ,

a_r^{τ} multiplier of the macro good price index for industrial energy backstop (τ = BY) or household energy backstop (τ = BC),

and

BY_{rt} ,BC_{rt} are the associated dual variables which indicate the activity levels of backstop energy production in region *r* and period *t* for industries or households.

Capital Stock Formation and Investment

An efficient allocation of capital, i.e. investment over time assures the following intertemporal zero-profit conditions which relates the cost of a unit of investment, the return to capital and the purchase price of a unit of capital stock in period *t:* [14]

$$\Pi_{rt}^{K} = p_{rt}^{K} - r_t^{K} - (1 - \delta)\, p_{r,t+1}^{K} = 0$$

and

$$\Pi_{rt}^{I} = p_{rt}^{I} - p_{r,t+1}^{K} \geq 0$$

where:

[14] The optimality conditions for capital stock formation and investment are directly derived from the maximization of lifetime utility by the representative household taking into account its budget constraint, the equation of motion for the capital stock and the condition that output in each period is either invested or consumed. Note that in our algebraic exposition we assume an investment lag of one period.

P_{rt}^{K} value (purchase price) of one unit of capital stock in region *r* and period *t*,

δ_r depreciation rate in region r,

p_{rt}^{I} cost of a unit of investment in period *t* which in our case equals p_{rt}^{A},

and

K_{rt} associated dual variable, which indicates the activity level of capital stock formation in region *r* and period *t,*

I_{rt} associated dual variable, which indicates the activity level of aggregate investment in region *r* and period *t* [15].

Market Clearance Conditions

Labor

The supply-demand balance for labor is:

$$\overline{L}_{rt} = Y_{rt} \frac{\partial \Pi_{rt}^{Y}}{\partial w_{rt}}$$

where:

$\overline{L}_{rt}$ exogenous endowment of time in region *r* and period *t.*[16]

Capital

The supply-demand balance for capital is:

$$K_{rt} = Y_{rt} \frac{\partial \Pi_{rt}^{Y}}{\partial v_{rt}}$$

Fuel-Specific Resources

The supply-demand balance for fuel-specific resources is:

$$\overline{Q}_{rt}^{ff} = F_{rt,ff} \frac{\partial \Pi_{rt,ff}^{F}}{\partial q_{rt}^{ff}} \qquad ff \in \{COA, OIL, GAS\}$$

where:

$\overline{Q}_{rt}^{ff}$ exogenous endowment with fuel-specific resource *ff* for region *r* and period *t.*

Fossil Fuels

The supply-demand balance for fossil fuels is:

[15] As written, we have taken explicit account of the non-negativity constraint for investment.

[16] Time endowment grows at a constant rate *g*, which determines the long-run (steady-state) growth rate of the economy.

$$\sum_r F_{rt}^{ff} = \left(\sum_r EY_{rt} \frac{\partial \Pi_{rt}^{EY}}{\partial (p_t^{ff} + pcarb_t CO2_{ff})} + EC_{rt} \frac{\partial \Pi_{rt}^{EC}}{\partial (p_t^{ff} + pcarb_t CO2_{ff})} \right) \qquad ff \in \{COA, OIL, GAS\}$$

Macro Output for Domestic Markets

The market clearance condition for the macro good produced for the domestic market is:

$$Y_{rt} \frac{\partial \Pi_{rt}^{Y}}{\partial p_{rt}} = A_{rt} \frac{\partial \Pi_{rt}^{A}}{\partial p_{rt}}$$

Macro Output for Export Markets

The market clearance condition for the macro good produced for the export market is:

$$Y_{rt} \frac{\partial \Pi_{rt}^{Y}}{\partial p_{rt}^{X}} = \sum_s A_{st} \frac{\partial \Pi_{st}^{A}}{\partial p_{st}^{X}}$$

Industrial Energy Aggregate

The market clearance condition for the industrial energy aggregate is:

$$EY_{rt} + BY_{rt} = EY_{rt} \frac{\partial \Pi_{rt}^{EY}}{\partial p_{rt}^{EY}}$$

Household Energy Aggregate

The market clearance condition for the household energy aggregate is:

$$EC_{rt} + BC_{rt} = EC_{rt} \frac{\partial \Pi_{rt}^{EC}}{\partial p_{rt}^{EC}}$$

Armington Aggregate

The market clearance condition for Armington aggregate is:

$$A_{rt} = Y_{rt} \frac{\partial \Pi_{rt}^{Y}}{\partial p_{rt}^{A}} + C_{rt} \frac{\partial \Pi_{rt}^{C}}{\partial p_{rt}^{A}} + I_r \frac{\partial \Pi_{rt}^{I}}{\partial p_{rt}^{A}} + BY_{rt} \frac{\partial \Pi_{rt}^{BY}}{\partial p_{rt}^{A}} + BC_{rt} \frac{\partial \Pi_{rt}^{BC}}{\partial p_{rt}^{A}}$$

Household Consumption Aggregate

The market clearance condition for the household consumption aggregate is:

$$C_{rt} = D_{rt}$$

where:

D_{rt} uncompensated final demand which is derived from maximization of lifetime utility (see below).

Income Balance of Households

Consumers choose to allocate lifetime income across consumption in different time periods in order to maximize lifetime utility. The representative agent in each period solves:

$$\text{Max} \sum_t \left(\frac{1}{1+\rho_r}\right)^t u_r(C_{rt})$$

$$\text{s.t.} \sum_t p_{rt}^C C_{rt} = M_r$$

where:

u_r instantaneous utility function of representative agent in region *r,*

ρ_r time preference rate of representative agent in region *r*,

and

M_r lifetime income of representative agent in region *r*.

Lifetime income M is defined as:

$$M_r = p_{r0}^K \overline{K}_{r0} + \sum_t w_{rt} \overline{L}_{rt} + \sum_{ff} q_{rt}^{ff} \overline{Q}_{rt}^{ff}$$

$$+ \sum_t \sum_{ff} pcarb_{rt} CO2_{ff} \left(EY_{rt} \frac{\partial \Pi_{rt}^{EY}}{\partial (p_t^{ff} + CO2_{ff}\, pcarb_{rt})} + EC_{rt} \frac{\partial \Pi_{rt}^{EC}}{\partial (p_t^{ff} + CO2_{ff}\, pcarb_{rt})} \right)$$

where:

$\overline{K}_{r0}$ initial capital stock in region *r*.

With isoelastic lifetime utility the instantaneous utility function is given as:

$$u_r(C_{rt}) = \frac{C_{rt}^{1-\frac{1}{\mu_r}}}{1-\frac{1}{\mu_r}}$$

where:

μ_r constant intertemporal elasticity of substitution.

The uncompensated final demand function D_{rt} is then derived as:

$$D_{rt}(p_{rt}^C, M) = \frac{(1+\rho_r)^{-t\mu_r}}{\sum_t (1+\rho_r)^{-t^{\mu_r}} p_{rt}^{C^{1-\mu_r}}} \frac{M}{p_{rt}^{C^{\mu_r}}}$$

Terminal Constraints

The finite horizon poses some problems with respect to capital accumulation. Without any terminal constraint, the capital stock at the end of the model's horizon would have no value and this would have significant repercussions for investment rates in the periods leading up to the end of the model horizon. In order to correct for this effect we define a terminal constraint which forces terminal investment to increase in proportion to final consumption demand:[17]

$$\frac{I_{Tr}}{I_{T-1,r}} = \frac{C_{Tr}}{C_{T-1,r}}.$$

Summary of Key Elasticities

Table A.1 summarizes the central values for key elasticities employed for the core simulations.

Table A.1: Overview of key elasticities

Type of elasticity	Description	Central Value
Armington elasticity of substitution	Degree of substitutability • Between macro imports from different regions • Between the import aggregate and the domestically produced macro good	 2 1
Armington elasticity of transformation	Degree of substitutability between macro good produced for the domestic market and macro good destined for the export market	2
Price elasticity of fossil fuel supply	Degree of response of international fossil fuel supply to changes in fossil fuel price	1 (coal), 4 (gas) 8 (oil)
Elasticity of substitution between non-energy and energy composite in production and final demand	This value increases linearly over time between a short-run value of 0.2 and the long-run value of 0.8 to reflect empirical evidence on differences between short-run and long-run adjustment costs (Lindbeck, 1983)	0.2 (short run: 2000) 0.8 (long run: 2050)
Interfuel elasticity of substitution	Degree of substitutability between fossil fuels (fuel switching)	0.5 (final demand) 2[a],1[b] (industry)

[a] between oil and gas [b] between coal and the oil-gas aggregate

[17] This constraint imposes balanced growth in the terminal period but does not require that the model achieves steady-state growth.

Appendix B: Suppression of *Hot Air*

Depending on the initial allocation of emission rights and the baseline (*BAU*) emission path for countries forming part of a multilateral greenhouse gas abatement agreement, emissions trading may lead to an effective increase of global emissions as compared to a regime under which all countries undertake purely domestic action. The *excess* emissions are referred to as *hot air* which occurs when countries whose *BAU* emissions are below their actual entitlements with emission rights sell *abundant* emission rights. In our C&C scenario hot air is produced in the *TRD* case since regions AFR, IDI and MEA sell emission rights which they do not use in the *NTR* case (see Figures 2a, c, e).

The overall welfare gains from trade then stem from two different sources. Firstly, the implicit relaxation of the global emission constraint due to hot air. Secondly, the gains from equalizing marginal abatement costs across countries. With respect to welfare comparison between the *NTR* and the *TRD* case, the difference in the environmental effect due to hot air would require some quantitative assessment of the economic benefits from emission reduction. As the latter is highly uncertain, one could alternatively assure consistent welfare analysis by forcing global emissions to the same trajectory across all scenarios.

In our case, we pick the emission level implied by the *NTR* case under C&C as the reference target level. In order to mitigate hot air, i.e. to keep the global emissions under *TRD* at the *NTR* level, we have to specify some (ad-hoc) rule how additional emissions in terms of hot air get counterbalanced. We introduce an endogenous variable that scales the entitlement with emission rights uniformly across all regions to assure that the global emission limit as determined for C&C under *NTR* will not be exceeded at any point in time.

Table B.1 provides a comparison of the welfare implications from emission trading with and without hot air. We see that suppression of hot air reduces the global efficiency gains of permit trading from 59 % to 53 % with respect to the *NTR* value. Likewise, the differences in welfare implications at the regional level are rather small; hot air countries slightly benefit from tightening the global emission constraint due to implicitly higher permit prices; the opposite applies to the other regions.

Table B.1: HEV in lifetime income (% change from *BAU*) for C&C – *NTR* versus *TRD*

	NTR	*TRD* Without hot air	*TRD* with hot air
AFR	-1.74	14.86	14.24
CHN	-2.35	-0.84	-0.74
IDI	0.16	15.52	15.15
LAM	-0.9	0.24	0.3
MEA	-2.6	2.04	2.03
NAM	-2.64	-2.34	-2.16
PAO	-1.17	-1.04	-0.96
PAS	-0.04	0.12	0.17
REC	-7.82	-7.5	-6.97
WEU	-1.34	-1.19	-1.1
WORLD	-1.82	-0.85	-0.75

Appendix C: Sensitivity Analysis

Tables C.1-C.4: Sensitivity analysis - HEV in lifetime income (% change from *BAU*)

Table C.1: Oil price responsiveness - oil supply elasticity (ε_r^{Oil})

	Low (12)		Central (8)		High (4)	
	NTR	*TRD*	*NTR*	*TRD*	*NTR*	*TRD*
AFR	-1.63	14.19	-1.74	14.24	-1.94	14.39
CHN	-2.34	-0.77	-2.35	-0.74	-2.38	-0.69
IDI	0.14	15.1	0.16	15.15	0.32	15.32
LAM	-0.81	0.33	-0.9	0.3	-1.06	0.22
MEA	-2.26	2.16	-2.6	2.03	-3.47	1.64
NAM	-2.65	-2.14	-2.64	-2.16	-2.63	-2.19
PAO	-1.18	-0.96	-1.17	-0.96	-1.14	-0.95
PAS	-0.09	0.14	-0.04	0.17	0.09	0.24
REC	-7.6	-6.84	-7.82	-6.97	-8.29	-7.31
WEU	-1.35	-1.1	-1.34	-1.1	-1.34	-1.08
WORLD	-1.81	-0.74	-1.82	-0.75	-1.86	-0.77

Table C.2: Energy demand responsiveness - short-run substitution elasticities (σ_r^{KLE} ; σ_r^{C})

	Low (0.1; 0.1)		Central (0.2; 02)		High (0.5; 0.5)	
	NTR	*TRD*	*NTR*	*TRD*	*NTR*	*TRD*
AFR	-1.74	14.58	-1.74	14.24	-1.75	13.65
CHN	-2.41	-0.73	-2.35	-0.74	-2.24	-0.65
IDI	0.16	15.45	0.16	15.15	0.16	14.67
LAM	-0.9	0.33	-0.9	0.3	-0.9	0.28
MEA	-2.57	2.11	-2.6	2.03	-2.64	1.93
NAM	-2.72	-2.24	-2.64	-2.16	-2.55	-2.06
PAO	-1.21	-1	-1.17	-0.96	-1.11	-0.9
PAS	-0.05	0.18	-0.04	0.17	-0.01	0.19
REC	-8.04	-7.15	-7.82	-6.97	-7.38	-6.59
WEU	-1.4	-1.14	-1.34	-1.1	-1.28	-1.04
WORLD	-1.88	-0.78	-1.82	-0.75	-1.76	-0.7

Table.C.3: Backstop costs*

	Low (4)		Central (6)		High (8)	
	NTR	*TRD*	*NTR*	*TRD*	*NTR*	*TRD*
AFR	-1.66	9.87	-1.74	14.24	-1.76	14.34
CHN	-2.04	-0.79	-2.35	-0.74	-2.35	-0.54
IDI	0.12	11.4	0.16	15.15	0.16	15.21
LAM	-0.85	0.11	-0.9	0.3	-0.92	0.32
MEA	-2.51	1.16	-2.6	2.03	-2.62	2.06
NAM	-1.77	-1.57	-2.64	-2.16	-3.04	-2.17
PAO	-0.79	-0.7	-1.17	-0.96	-1.3	-0.96
PAS	-0.02	0.17	-0.04	0.17	-0.05	0.18
REC	-6.31	-5.58	-7.82	-6.97	-7.74	-6.98
WEU	-0.86	-0.77	-1.34	-1.1	-1.53	-1.1
WORLD	-1.31	-0.58	-1.82	-0.75	-2.02	-0.74

* For the central case, the backstop fuel is assumed to cost six times (6) the 2000 fossil fuel energy aggregate price.

Table C.4: Non-energy trade impacts - Armington elasticities (σ_r^A ; σ_r^M)

	Low (0.75;1.5)		Central (1;2)		High (1.5;3)	
	NTR	*TRD*	*NTR*	*TRD*	*NTR*	*TRD*
AFR	-3.27	16.03	-1.74	14.24	-1.25	13.54
CHN	-2.91	0.53	-2.35	-0.74	-2.39	-1.68
IDI	0.69	17.67	0.16	15.15	0.62	14.15
LAM	-2.12	-0.09	-0.9	0.3	-0.61	0.18
MEA	-7.38	-0.17	-2.6	2.03	-2.03	1.9
NAM	-2.57	-2.34	-2.64	-2.16	-2.63	-2.11
PAO	-1.04	-0.9	-1.17	-0.96	-1.18	-0.94
PAS	0.26	0.96	-0.04	0.17	0.13	-0.11
REC	-10.03	-8.6	-7.82	-6.97	-7.78	-7.04
WEU	-1.26	-1.05	-1.34	-1.1	-1.36	-1.06
WORLD	-2.1	-0.77	-1.82	-0.75	-1.76	-0.81

References

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

Böhringer, C. and T.F. Rutherford (2001), World Economic Impacts of the Kyoto Protocol, in: P.J.J.Welfens (Ed.), Internationalization of the Economy and Environmental Policy Options, Springer, Berlin, 161-180.

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

Lindbeck, A. (1983), The Recent Slowdown of Productivity Growth, *Economic Journal*, 1983.

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.