Rio - 10 Years After:

A Critical Appraisal of Climate Policy

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Abstract

Ten years after the initial Climate Change Convention from Rio in 1992, the developed world is likely to ratify the Kyoto Protocol, which has been celebrated as a milestone in climate protection. Standard economic theory, however, casts doubt that Kyoto will go beyond symbolic policy. In this paper we show that the final concretion of the Kyoto Protocol obeys the theoretical prediction: Kyoto more or less boils down to business-as-usual without significant compliance costs to ratifying parties.

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1. Introduction

In 2002, ten years after the Climate Convention was adopted at the Rio Earth Summit, the world community is expected to implement a legally binding international agreement on climate protection on the occasion of the forthcoming Earth Summit in Johannesburg. This agreement goes back to the 3rd Conference of Parties (COP3) to the Climate Convention in 1997 in Kyoto where industrialized nations committed themselves to reducing their emissions of greenhouse gases by roughly 5 % on average as compared to their 1990 emission levels during the commitment period from 2008 to 2012 (UNFCCC 1997). The so-called Kyoto Protocol has been celebrated as a breakthrough in international climate policy, because it implied - in its original form - substantial emission reductions in the industrialized countries (as listed in Annex B of the Protocol) vis-à-vis business-as-usual emissions.

From the stance of standard economic theory, such an agreement with potentially large economic adjustment costs to industrialized nations is hard to explain. Climate protection constitutes the case of voluntarily providing a pure global public good which entails serious incentive problems. In fact, according to standard game theory, no country should have an incentive to abate greenhouse gas emissions above its non-cooperative level. In the short- to medium-run, the latter can be identified as the business-as-usual emission level, since costs of emission abatement occur instantly but (rather uncertain) benefits will only arise in the far distant future.

In this paper, we investigate whether the final outcome of 10 years of climate change negotiations obeys the theoretical prediction of standard economic theory. We show that recent changes to the Kyoto Protocol - most notably, U.S. withdrawal, credits for carbon dioxide sinks, and unrestricted emissions trading - in fact boil down climate policy to business-as-usual without any compliance costs for participating countries. At second glance, however, it appears that uncertainties on market power and future economic development may turn the Kyoto Protocol into an agreement with effective emission abatement and economic costs. Based on quantitative evidence from an established large-scale multi-region model of global trade and energy use, we argue that the predictive power of standard economic theory still holds, because the costs arising from these uncertainties are rather negligible.

Several studies have already pointed out that the recent amendments to the Kyoto Protocol have substantially watered down its environmental effectiveness (see Buchner et al. 2001 for a synopsis). However, none of the studies links quantitative results to the prediction of standard economic theory in a rigorous and comprehensive way. Our analysis combines several innovations such as market power in permit trade, or terms-of-trade effects, and proves robustness of our qualitative conclusions with respect to the wide range of uncertainties on baseline development and key elasticities.

2. The Kyoto Protocol at first view: What theory predicts!

Climate protection poses the problem of providing a global public good. Each country has to decide on how much abatement of greenhouse gas emissions it wants to undertake. In the absence of any supranational authority, countries behave non-cooperatively, i.e. each country decides according to a comparison of its own benefits from abatement and its own costs of abatement.

Let there be *n* countries and let q_i denote the abatement level of country *i*. Global abatement, then, simply amounts to $Q = \sum_i q_i$. National benefits from abatement depend on the global abatement level, hence $B_i = B_i\left(Q\right)$, while costs depend on the national abatement level that a single country chooses: $C_i = C_i\left(q_i\right)$. In this framework, non-cooperative behavior simply means that countries try to maximize their own net benefit from abatement. The first order condition to the optimization problem is given by $B_i' = C_i'$, i.e. countries choose abatement levels that equate their own marginal benefits from abatement and their own marginal abatement costs. In the literature, this solution is referred to as the non-cooperative equilibrium of the n-countries global public good game or the Nash-Cournot outcome (Finus 2001). The non-cooperative equilibrium is suboptimal from a global planner point of view, because the decentralized national decision maker does not recognize the positive externalities spread on all other countries by its own abatement action. Furthermore, each country has an incentive to free ride on abatement in other countries without contributing by its own, which leads to the well-known prisoner's-dilemma situation in climate policy.

For the purpose of our paper, it is necessary to quantify the compliance costs a country is willing to accept in the non-cooperative solution. These costs can be assumed to be (close to) zero. Apart from the classical free-rider incentive, the main reason is that for the problem of mitigating global warming, abatement measures undertaken today will not unfold a stabilizing climate effect until far in the future. Hence, benefits from climate protection will accrue to future generations, while costs have to be carried by the current generation. In formal terms, $B_i\left(Q\right) \simeq 0$ and hence $C_i\left(q_i\right) = 0$. Any rational government, thus, will not enter an international agreement which is likely to impose significant costs.

Prima facie, the effective outcome of the Kyoto Protocol - after 5 years of negotiation - backs our simple theoretical argument. Table 1 provides the quantitative evidence. The Kyoto Protocol negotiated in 1997 during the third Conference of Parties (COP3), requires industrialized countries to limit their emissions of greenhouse gases (GHG). The limits have been set with reference to 1990 emission levels.

Table 1: Baseline emissions, percentage reduction, absolute cutbacks[1]

Region	Baseline Emissions (MtC)[a]		Nominal Reduction (% wrt 1990)[b]		Effective Reduction (% wrt 2010)		Absolute Cutback (MtC wrt 2010)	
	1990	2010	*OLD*	*NEW*	*OLD*	*NEW*	*OLD*	*NEW*
AUN	88	130	-6.8	-10.2	27.7	25.4	36	33
CAN	127	165	6.0	-7.9	27.7	17.0	46	28
EUR	929	1041	7.8	5.2	17.7	15.4	184	160
JPN	269	331	6.0	0.8	23.6	19.4	78	64
CEA	301	227	7.1	3.9	-23.2	-27.5	-53	-62
FSU	1036	713	0.0	-6.4	-45.3	-54.6	-323	-389
Total US out[c]	2750	2607	5.0	0.5	-0.7	-3.8	-32	-166
USA	1347	1809	7.0	3.2	30.8	27.9	556	505
Total US in[d]	4097	4416	5.0	0.5	11.9	7.7	525	339

Key: AUN – Australia and New Zealand, CAN – Canada, EUR - OECD Europe (incl. EFTA), JPN – Japan, CEA - Central and Eastern Europe, FSU - Former Soviet Union (incl. Ukraine).

[a] Based on the IEO (2001): reference case
[b] Estimates by the European Commission (Nemry 2001)
[c] Annex-B without U.S. compliance
[d] Annex-B with U.S. compliance

Column “Baseline Emissions - 1990” of Table 1 lists the historic emissions for all Annex B regions, while column “Nominal Reduction – *OLD*” provides the reduction targets as originally foreseen by the Protocol.

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[1] For reasons of data availability, we apply the GHG reduction targets to CO_2 only, which is by far the most important GHG among industrialized countries.

The reduction targets with respect to 1990 are only *nominal* in the sense that they apply to historic emission levels. Since these targets will not become legally binding before the Kyoto commitment period (2008-2012), the appropriate reference for the *effective* cutback requirements are the business-as-usual (*BaU*) emissions during the commitment period. Column “Baseline Emissions - 2010” reports the projected *BaU* emissions for the central year 2010 based on the reference scenario of the most recent International Energy Outlook (IEO 2001) by the U.S. Department of Energy. Except for the economies in transition, which include Central and Eastern Europe (CEA) as well as the Former Soviet Union (FSU), the nominal commitments translate into much more stringent reduction requirements, since industrialized countries are projected to have economic growth accompanied by a considerable increase in GHG emissions from fossil fuel combustion. For example, Australia and New Zealand (AUN) receive emission rights that are roughly 7 % higher than their 1990 reference emission levels, but in 2010 they will nevertheless face an effective cutback requirement of nearly 28 % vis-à-vis their *BaU* emissions. Apparently, the economies in transition have been endowed with emission entitlements under the Kyoto Protocol that are well in excess of their anticipated future *BaU* emissions.[2] As will be elaborated below, the availability of these excess emissions, referred to as “hot air”, will crucially affect the potential compliance costs of OECD countries under the Kyoto Protocol.

Column “Absolute Cutback – *OLD*” converts the effective percentage reduction into absolute cutback requirements. An assessment of Table 1 with respect to the implementation of the Kyoto Protocol in its original form (i.e. U.S. compliance and *OLD* targets) indicates that the Kyoto Protocol demands a substantial cutback of *BaU* emissions for the industrialized world. Even in the case of unrestricted Annex B trade in emission rights, which would allow for the full availability of hot air from CEA and FSU, aggregate Annex B emissions are supposed to fall by roughly 12 % as compared to *BaU* (see intersection of row “Total US in” with column “Effective Reduction - *OLD* ” in Table 1).

More recently, however, there have been two major changes to the Kyoto Protocol which – at first sight – will boil it down to *BaU* without any compliance costs to ratifying countries.

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[2] Obviously, hot air decreases the environmental effectiveness and economic costs of the Kyoto Protocol vis-à-vis strictly domestic action. Concerns on the loss in environmental effectiveness due to hot air have motivated intense debates between negotiating parties on the permissible scope of permit trade (see e.g. Baron et al. 1999).

In March 2001, the U.S. under President Bush, declared its withdrawal from the Protocol, reasoning that the costs to the U.S. economy would be too high and exemption of developing countries from binding emission targets would not be acceptable.[3] U.S. withdrawal had a crucial impact on the most recent climate policy negotiations at Bonn (June 2001) and Marrakech (October 2001). Due to the "double trigger" mechanism[4], entry into force of the Kyoto Protocol is no longer possible without participation of FSU and country group of AUN, CAN and JPN. Using their implicit veto power, these regions achieved major revisions to the initial settings of the Kyoto Protocol: Not only have the original emission reduction targets been considerably softened by conceding substantial credits for carbon dioxide sinks (see columns "*NEW*" in Table 1) but proposals for explicit restrictions to permit trade (in order to suppress hot air) also have been dropped.

In Table 1, the last three rows illustrate the dramatic implications of U.S. withdrawal for the effectiveness of the Kyoto Protocol. Without U.S. compliance, the effective aggregate cutback requirement of the remaining Annex B countries falls below zero, i.e. U.S. withdrawal implies an excess supply of hot air. Given full tradability of emission rights across Annex B regions, competitive permit markets drive down the international permit price to zero such that no emission reduction at all will occur with respect to *BaU*.

The Kyoto Protocol comes at no costs to ratifying parties, because it effectively boils down to business-as-usual without binding emission constraint. We simply see what standard economic theory predicts.

3. At second glance: Kyoto is different from *BaU* but not much!

3.1 Market power and baseline projections

A more thorough assessment of the Kyoto Protocol reveals two major uncertainties that warrant caution against our simple back-on-the-envelope calculation.

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[3] Note that irrespective of this move under the Bush administration, the prospects for U.S. ratification of the Kyoto Protocol have been rather small over the years. The reason is the Byrd-Hagel resolution, which makes "meaningful" participation of developing countries a *conditio sine qua non* for ratification, and has been passed unanimously by the U.S. Senate in 1997 (The Byrd-Hagel Resolution, U.S. Senate, 12 June 1997, 105th Congress, 1st Session, Senate Resolution 98). U.S. ratification of the Kyoto Protocol would require a 2/3 majority in the Senate.

[4] On the one side, at least 55 countries have to ratify the treaty through their national parliaments. On the other side, those countries which ratify the treaty have to account for at least 55 % of the CO_2 emissions in 1990 (the Protocol's base year).

First, the assumption of perfectly competitive permit markets where the international permit price falls to zero and emission sales do not create any revenues seems to be implausible (Westkog (1996), Woerdman (2000)). In general, the likelihood of market power increases if the number of participants is smaller or if the size of some participants is larger than neo-classical firm-to-firm trading with many participants. Article 17 of the Kyoto Protocol creates an intergovernmental emissions trading market next to or in lieu of firm trading, so it is uncertain whether firms or governments will participate in international emissions trading. In the case of firm-to-firm trading, the scope for market power seems rather limited. However, it is unlikely that as FSU as the dominant supplier of emission rights (due to large entitlements with hot air) will give up market power by leaving permit trade to its domestic firms. On the demand side, competitive behavior seems to be the appropriate assumption: Either firms of OECD countries may be allowed to engage in emissions trading directly[5], or because - under the assumption of Party-to-Party trading - the coordination of several individual OECD countries within a demand cartel will be rather difficult. As a monopolist, FSU will reduce its permit supply and charge a mark-up over its marginal abatement costs (which are zero for hot air) to maximize profits. The international permit price will no longer be zero (as in the competitive case above) imposing non-zero compliance costs on industrialized countries with positive cutback requirements.

Second, a different perspective on how economies and emissions will evolve in the future might imply an effective demand in emission rights compared to a situation with an excess permit supply as suggested by Table 1. Since abatement costs associated with the implementation of the Kyoto emission constraints crucially depend on the business-as-usual (*BaU*) projections for GDP and emissions (see e.g. Böhringer, Jensen and Rutherford 2002), any careful analysis of the potential costs associated with the implementation of the Kyoto Protocol requires sensitivity analysis with respect to alternative baseline projections.

3.2 Assessing the costs of compliance

Market power and alternative baseline projections could significantly alter the economic costs of implementing Kyoto such that our initial conclusion might fail. Our main interest, then, is to assess how much the implied costs for major Annex B parties differ from

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[5] See e.g. the plans of the EU commission to implement an EU internal trading system starting in 2005 with firm-to-firm trading across energy-intensive industries (COM 2000).

zero when market power and alternative baselines are taken into account. In order to obtain such cost estimates, we make use of a computable general equilibrium model of world trade and energy use. The general equilibrium approach provides a consistent and comprehensive framework for studying price-dependent interactions between the energy system and the rest of the economy. This is important, since carbon abatement policies not only cause direct (partial equilibrium) adjustments on fossil fuel markets but also produce important (general equilibrium) indirect spillovers to other markets. Therefore, 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 Weyant 1999 for a recent survey).

The concrete 7-sector, 8-region CGE model underlying our analysis has been widely used in the past to quantify the economic impacts of GHG abatement (Böhringer 2000, Rutherford and Paltsev 2000, Böhringer 2002, Böhringer and Rutherford 2002). In the standard model version, all factor and commodity markets are assumed to be competitive. For our simulations, we drop this assumption with respect to emissions trading and treat FSU as a monopoly supplier of emission permits. Profit-maximizing behavior then entails the equalization of marginal abatement cost and perceived marginal revenue, which implies that the permit price set by FSU is a markup on marginal cost. Obviously, the markup rate is a decreasing function of the price elasticity of permit demand. Since the concrete formula for the endogenous price elasticity is analytically intractable, we represent the mark-up in the model as an export tariff that drives a wedge between the international permit price and the marginal abatement costs in FSU. The mark-up has the same effect as a quota on the sales of permits where the quota rents accrue to FSU. In order to determine the optimal tariff or quota numerically, we raise the tariff of FSU in sufficiently small steps and then identify that rate which maximizes its welfare.

For the sake of brevity, we abstain here from presenting details of sectoral and regional aggregation as well as the comprehensive description of the model algebra and model parameterization, which are fully available as an Internet download from ftp://ftp.zew.de/pub/zew-docs/div/rio+10.pdf.[6] As is customary in applied general equilibrium analysis, the model is based on economic transactions in a particular benchmark year (1997 in our case). Benchmark data determine parameters of the functional forms from a given set of

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[6] The data and model to replicate all of our results can be obtained from the authors upon request.

benchmark quantities, prices, and elasticities (see Table A.1 in the download for a summary of central values for key elasticities). As to benchmark quantities and prices, we employ the GTAP-EG database as described in Rutherford and Paltsev (2000).

The magnitude and distribution of abatement costs associated with the implementation of the Kyoto emission constraints crucially depend on the business-as-usual (*BAU*) projections for GDP, fuel prices, energy efficiency improvements, etc. In our comparative-static framework, we infer the *BAU* economic structure of the model's regions for the year 2010 using projections by the U.S. Department of Energy (DOE 1998) for GDP growth, fossil fuel production, and future energy prices. We incorporate autonomous energy efficiency improvement factors which scale energy demand functions to match the exogenous DOE emission forecasts. In our simulations, we measure the economic and environmental consequences of abatement policies with respect to the *BaU* situation in 2010.

Table 2 summarizes the main economic and environmental effects of four abatement scenarios which reflect the recent history of climate change negotiations after the signature of the Kyoto Protocol in 1997. Scenario *NTRin_OLD* considers the implementation of the Kyoto Protocol based on the original reduction targets, U.S. compliance and fully domestic action (i.e. no trade in emission rights). Emission constraints as originally mandated under the Kyoto Protocol induce non-negligible adjustment costs to OECD countries. The reason is that emission targets, which are stated with respect to 1990, translate into much higher *effective* carbon reduction requirements with respect to business-as-usual emission levels during the Kyoto budget period between 2008-2012. Without "where"-flexibility, the effective emission constraints require substantial changes in the production and consumption patterns of OECD countries towards less carbon-intensity, which induces a loss of productivity and real income (consumption). Adjustment costs – measured in percentage loss of *BaU* consumption – range from 0.17 % for EUR to 1.48 % for CAN indicating regional differences in the effective cutback requirements, carbon intensities of economies, the ease of carbon substitution within production and consumption, and indirect losses or benefits through terms-of-trade effects.[7] The latter are the reason why CEA and FSU as well as non-Annex B countries (ROW) are affected by abatement policies of trading partners even though they do not face a binding emission constraint.

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[7] For a detailed discussion of the sources and magnitude of terms-of-trade effects from carbon abatement see Böhringer and Rutherford (2002).

Table 2: Economic and environmental impacts of implementing the Kyoto Protocol

	NTRin_OLD	*NTRout_OLD*	*NTRout_NEW*	*TRDout_NEW*
	Consumption change in % vs. *BaU*			
AUN	-1,18	-1,09	-0,93	-0,29
CAN	-1,48	-0,62	-0,29	-0,13
EUR	-0,17	-0,24	-0,19	-0,06
JPN	-0,26	-0,34	-0,22	-0,05
CEA	0,49	0,27	0,22	0,75
FSU	-0,93	-0,69	-0,59	0,38
USA	-0,51	0,01	0,01	0,00
ROW	-0,35	-0,19	-0,15	-0,03
TOTAL	-0,24	-0,12	-0,09	-0,01
	Marginal abatement costs in USD$_{97}$ per ton of carbon			
AUN	126	123	106	18
CAN	145	132	64	18
EUR	111	106	87	18
JPN	183	176	129	18
CEA	0	0	0	18
FSU	0	0	0	0
USA	156	-	-	-
	Consumption change in USD$_{97}$ per capita			
AUN	-114	-107	-90	-28
CAN	-162	-68	-32	-15
EUR	-23	-31	-24	-8
JPN	-53	-67	-43	-9
CEA	8	4	3	12
FSU	-12	-9	-7	5
USA	-92	-	-	-
	Emission reduction in % vs. *BaU*			
TOTAL	9,6	2,8	2,3	0,7

Terms-of-trade effects work primarily through the decline of international fuel prices following the drop in energy demand under emission reduction policies: Net fuel importers such as CEA benefit from cheaper energy imports, while FSU and ROW, which are net fuel exporters, are negatively affected. As has been elaborated by Böhringer and Rutherford (2002) indirect terms-of-trade effects account for a substantial share of the total economic impact on abating countries. Direct abatement costs of CAN, for example, are significantly magnified by reduced revenues from fossil fuel exports.

Converting the percentage changes in consumption into implicit payments per capita, the specific costs for abating OECD regions range from 23 USD/capita of EUR to 162 USD/capita for CAN. The compliance costs for the U.S. amounts to 92 USD. As we can see from column *NTRout_OLD*, non-compliance of the U.S. leaves the remaining OECD countries with considerable costs although fuel exporting regions *AUN* and, particularly, *CAN*, benefit from U.S. withdrawal through a smaller drop in world energy prices.

As noted in the preceding section, U.S. withdrawal has triggered two further concretions to the Kyoto Protocol. First, a generous accounting of carbon sink credits has been approved.[8] Second, remaining parties have implicitly agreed on unrestricted Annex B emissions trading.

The scenario *NTRout_NEW* shows that sink credits considerably reduce compliance costs, but the effective burden is still significant (with up to 90 USD per capita for AUN) if regions meet their targets through domestic action.

The drastic drop in costs for OECD countries comes from unrestricted Annex B emissions trading as captured in scenario *TRDout_NEW*, where we account for market power by FSU.[9] Although compliance costs for OECD countries are still different from zero, comparison of cost figures under the initial Kyoto setting (*NTRin_OLD*) and its final concretion clearly backs our initial proposition that Kyoto should come close to business-as-usual. Note in this context that the cost figures reported for monopolistic permit trade must be seen as an upper bound since we do not account for firm-to-firm trading or the Clean Developing Mechanism (CDM) that allows the purchase of emission credits from abatement in non-Annex B developing countries.

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[8] The striking example is Russia. In addition to hot air, the Russian forest management sink quota under Article 3.4 of the Kyoto Protocol was increased from 17.63 Mt carbon per year to 33 Mt at COP7 in Marrakech although it was clear that these credits are oversized. Obviously, Russia took advantage of its bargaining power, since – after U.S. withdrawal – the Kyoto Protocol would fail without Russian ratification (N.B.: The Kyoto agreement will not enter into force until it has been ratified by at least 55 countries, and these ratifying countries must have contributed at least 55 % of the industrialized world's CO_2 emissions in 1990).

[9] With Annex B emissions trading CEA and FSU do substantially better than under *BaU* since they can capitalize on larger amounts of hot air.

In line with the decrease in compliance costs, global environmental effectiveness drops towards zero when we incorporate step by step the changes to the initial Protocol. Based on the quantitative evidence from Table 2, we conclude that Kyoto is *different* from *BaU*, but *not much*.

Table 3: Implications of alternative baseline projections (*TRDout_NEW*)

	LOW	*REFERENCE*	*HIGH*
		Consumption change in % vs. *BaU*	
AUN	-0,13	-0,29	-0,35
CAN	-0,05	-0,13	-0,18
EUR	-0,02	-0,06	-0,09
JPN	-0,01	-0,05	-0,07
CEA	0,38	0,75	0,68
FSU	0,09	0,38	0,60
USA	0,00	0,00	0,00
ROW	-0,02	-0,03	-0,03
TOTAL	-0,01	-0,01	-0,02
		Marginal abatement costs in USD_{97}	
AUN	7	18	22
CAN	7	18	22
EUR	7	18	22
JPN	7	18	22
CEA	7	18	22
FSU	0	0	0
USA	-	-	-
		Consumption change in USD_{97} per capita	
AUN	-14	-28	-34
CAN	-6	-15	-21
EUR	-3	-8	-11
JPN	-2	-9	-14
CEA	7	12	12
FSU	1	5	7
USA	-	-	-
		Emission reduction in % vs. *BaU*	
TOTAL	0,3	0,7	1,0

The results of Table 2 are based on the reference scenario of the most recent International Energy Outlook (IEO 2001). In addition, IEO reports extensive data for projections where the growth potential of the world economy is considered either more pessimistic (case: *LOW*) or more optimistic (case: *HIGH*). Lower economic growth is linked to lower demands for fossil fuels and lower *BaU* carbon emissions. The opposite applies for higher economic growth. Table 3 provides a condensed summary of results for alternative baseline projections focusing on scenario *TRDout_NEW*, which reflects the final concretion of the Kyoto Protocol. As expected, the nominal Kyoto reduction targets translate into less stringent emission constraints for the *LOW* case and more stringent reduction requirements for the *HIGH* case, resulting in respectively lower or higher compliance costs for OECD countries. Conversely, CEA and FSU do better for the *HIGH* case than for the *LOW* case, because they draw higher profits from the sales of emission rights.

3.3 Sensitivity analysis

To evaluate the sensitivity of our general equilibrium estimates to uncertainties in the elasticity space, we conducted 1000 Monte Carlo simulations. In each simulation, values for six elasticties (trade elasticities, energy demand elasticities and fossil fuel supply elasticities) that are key determinants for the economic adjustment costs to emission constraints were drawn from uniform probability distributions around the model central values (see Table A.1 in the download).

Table 4 provides a statistical summary of results. For each of the scenarios, we have listed the core (central case) values together with the mean and the median as well as the 5 % quantile and 95 % quantile. The central case effects are close to the mean and median values. Based on our sample distribution, there is a 90 % probability that (marginal and inframarginal) adjustment costs and global emission reduction lie between the values indicated by the 5 % and 95 % quantile. Although we observe some spread, in particular for the scenarios without emission trading, that stand out for stronger overall adjustment effects, all of our insights based on the central case general equilibrium estimates remain robust even when we account for substantial uncertainty in the parameterization space.

Table 4: Results of Monte Carlo simulation

	NTRin_OLD					***NTRout_OLD***					***NTRout_NEW***					***TRDout_NEW***				
	core value	mean	median	5% quantile	95% quantile	core value	mean	median	5% quantile	95% quantile	core value	mean	median	5% quantile	95% quantile	core value	mean	median	5% quantile	95% quantile
Consumption change in % vs. *BaU*																				
AUN	-1,18	-1,16	-1,14	-1,38	-1,01	-1,09	-1,07	-1,06	-1,30	-0,91	-0,93	-0,92	-0,91	-1,10	-0,78	-0,29	-0,27	-0,27	-0,33	-0,23
CAN	-1,48	-1,43	-1,42	-1,59	-1,31	-0,62	-0,64	-0,63	-0,76	-0,55	-0,29	-0,29	-0,29	-0,32	-0,26	-0,13	-0,13	-0,13	-0,15	-0,12
EUR	-0,17	-0,19	-0,20	-0,23	-0,14	-0,24	-0,26	-0,26	-0,29	-0,22	-0,19	-0,20	-0,20	-0,22	-0,17	-0,06	-0,06	-0,06	-0,07	-0,05
JPN	-0,26	-0,31	-0,31	-0,38	-0,21	-0,34	-0,38	-0,39	-0,46	-0,28	-0,22	-0,25	-0,26	-0,30	-0,18	-0,05	-0,05	-0,05	-0,05	-0,04
CEA	0,49	0,50	0,50	0,29	0,73	0,27	0,30	0,30	0,16	0,45	0,22	0,24	0,24	0,12	0,36	0,75	0,67	0,64	0,46	0,95
FSU	-0,93	-0,88	-0,87	-1,04	-0,74	-0,69	-0,64	-0,63	-0,79	-0,53	-0,59	-0,54	-0,54	-0,67	-0,45	0,38	0,38	0,37	0,29	0,50
USA	-0,51	-0,56	-0,53	-0,78	-0,42	0,01	0,01	0,01	0,00	0,03	0,01	0,01	0,01	0,00	0,02	0,00	0,00	0,00	0,00	0,01
ROW	-0,35	-0,31	-0,30	-0,42	-0,24	-0,19	-0,17	-0,16	-0,23	-0,13	-0,15	-0,14	-0,13	-0,18	-0,11	-0,03	-0,03	-0,03	-0,04	-0,02
TOTAL	-0,24	-0,25	-0,25	-0,31	-0,21	-0,12	-0,13	-0,13	-0,14	-0,12	-0,09	-0,09	-0,09	-0,10	-0,09	-0,01	-0,01	-0,01	-0,02	-0,01
Marginal abatement costs in USD$_{97}$ per ton of carbon																				
AUN	126	135	124	92	207	123	132	120	89	203	106	113	104	77	172	18	17	17	14	20
CAN	145	154	145	112	222	132	137	130	99	197	64	65	63	51	87	18	17	17	14	20
EUR	111	114	110	88	149	106	108	104	83	143	87	88	85	69	115	18	17	17	14	20
JPN	183	191	181	139	270	176	184	173	133	262	129	133	127	100	183	18	17	17	14	20
CEA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	17	17	14	20
FSU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
USA	156	170	156	114	271	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consumption change in USD$_{97}$ per capita																				
AUN	-114	-113	-110	-134	-99	-107	-104	-103	-128	-86	-90	-89	-86	-107	-76	-28	-26	-28	-31	-21
CAN	-162	-155	-153	-174	-141	-68	-70	-68	-82	-59	-32	-32	-32	-35	-29	-15	-14	-15	-15	-12
EUR	-23	-25	-26	-31	-18	-31	-33	-34	-38	-29	-24	-26	-26	-29	-22	-8	-8	-8	-8	-7
JPN	-53	-61	-61	-76	-43	-67	-76	-76	-91	-57	-43	-50	-51	-59	-35	-9	-10	-9	-10	-9
CEA	8	8	8	5	12	4	5	5	2	7	3	4	4	2	6	12	11	11	7	16
FSU	-12	-11	-11	-13	-9	-9	-8	-8	-10	-6	-7	-7	-6	-8	-5	5	5	4	3	6
USA	-92	-102	-96	-142	-76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Emission reduction in % vs. *BaU*																				
TOTAL	9,60	9,51	9,50	9,00	10,00	2,80	2,71	2,70	2,40	3,00	2,30	2,22	2,20	1,90	2,50	0,70	0,69	0,70	0,60	0,80

4. Conclusion

Ten years after the initial Climate Change Convention from Rio in 1992, the developed world is likely to ratify the Kyoto Protocol which sets legally binding emission reduction targets to industrialized countries. Climate policy makers have already celebrated the forthcoming ratification of the Kyoto Protocol as a milestone in climate protection. Standard economic theory, however, casts doubt that Kyoto will go beyond symbolic policy. Climate protection corresponds to the voluntary provision of a global public good, exhibiting severe incentive problems. Moreover, the benefits of emission abatement arise in the far distant future, while abatement costs have to be borne by the current generations.

In this paper, we have quantified the final outcome of the Kyoto Protocol in economic and environmental terms to compare it with the theoretical prediction. We have shown that uncertainties on the future economic development and market power in emissions trading might prevent Kyoto from boiling down to purely symbolic policy. However, even for high growth projections and extreme assumptions on market power, Kyoto is not much different from business-as-usual without effective emission constraint. The residual costs for OECD countries complying to the Kyoto Protocol are rather small and may reasonably be interpreted as governments’ willingness to appease voters who want to see some climate policy action but are not willing to pay much.

Few would denigrate the importance of Kyoto in terms of achieving a broad-based international voluntary agreement. As a matter of fact, the Kyoto process has established a framework that may simplify the negotiation of future global climate protection strategies. However, it must be kept in mind that the Kyoto Protocol has not resolved any of the fundamental incentive problems inherent to the voluntary provision of climate protection as a pure global public good. Consequently, policies that aim at more effective treaties must push for institutional settings that promote international cooperation. Economic theory has proposed several instruments such as issue-linkage or sanction mechanisms but complementary applied research must focus on identifying which of these instruments are likely to provide concrete improvements in practice.

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Appendix A: Detailed Algebraic Model Description

This section outlines the main characteristics of a generic static general equilibrium model of the world economy designed for the medium-run economic analysis of carbon abatement constraints. It is a well-known Arrow-Debreu model that concerns the interaction of consumers and producers in markets. Consumers in the model have a primary exogenous endowment of the commodities and a set of preferences giving demand functions for each commodity. The demands depend on all prices; they are continuous and non-negative, homogenous of degree zero in factor prices and satisfy Walras’ Law, i.e. the total value of consumer expenditure equals consumer income at any set of prices. Market demands are the sum of final and intermediate demands. Producers maximize profits given a constant returns to scale production technology. Because of the homogeneity of degree zero of the demand functions and the linear homogeneity of the profit functions in prices, only relative prices matter in such a model. Two classes of conditions characterize the competitive equilibrium in the model: market clearance conditions and zero profit conditions. In equilibrium, price levels and production levels in each industry are such that market demand equals market supply for each commodity. Profit maximization under a constant returns to scale technology implies that no activity does any better than break even at equilibrium prices. The model is a system of simultaneous, non-linear equations with the number of equations equal to the number of variables.

A.1 Production

Within each region (indexed by the subscript *r*), each producing sector (indexed interchangeable by *i* and *j*) is represented by a single-output producing firm which chooses input and output quantities in order to maximize profits. Firm behavior can be construed as a two-stage procedure in which the firm selects the optimal quantities of primary factors *k* (indexed by *f*) and intermediate inputs *x* from other sectors in order to minimize production costs given input prices and some production level $Y = \varphi(k,x)$.

The second stage, given an exogenous output price, is the selection of the output level *Y* to maximize profits. The firm’s problem is then:

$$\underset{y_{jir},x_{jir},k_{fir}}{Max} \ \Pi_{ir} = p_{ir} \cdot Y_{ir} - C_{ir}\left(p_{jr}, w_{fr}, Y_{ir}\right) \ \ s.t. \ Y_{ir} = \varphi_{ir}\left(x_{jir}, k_{fir}\right) \qquad [1]$$

where Π denotes the profit functions, C the cost functions which relate the minimum possible total costs of producing Y to the positive input prices, technology parameters, and the output quantity Y, and p and w are the prices for goods and factors, respectively.

Production of each good takes place according to constant elasticity of substitution (CES) production functions, which exhibit constant returns to scale. Therefore, the output price equals the per-unit cost in each sector, and firms make zero profits in equilibrium (Euler's Theorem). Profit maximization under constant returns to scale implies the equilibrium condition:

$$\pi_{ir} = p_{ir} - c_{ir}(p_{jr}, w_{fr}) = 0 \quad \text{(zero profit condition)} \qquad [2]$$

where c and π are the unit cost and profit functions, respectively.

Demand functions for goods and factors can be derived by Shepard's Lemma. It suggests that the first-order differentiation of the cost function with respect to an input price yields the cost-minimizing demand function for the corresponding input. Hence, the intermediate demand for good j in sector i is:

$$x_{jir} = \frac{\partial C_{ir}}{\partial p_{jr}} = Y_{ir} \cdot \frac{\partial c_{ir}}{\partial p_{jr}} \qquad [3]$$

and the demand for factor f in sector i is:

$$k_{fir} = \frac{\partial C_{ir}}{\partial w_{fr}} = Y_{ir} \cdot \frac{\partial c_{ir}}{\partial w_{fr}} \qquad [4]$$

The profit functions possess a corresponding derivative property (Hotelling's Lemma):

$$x_{jir} = \frac{\partial \Pi_{ir}}{\partial p_{jr}} = Y_{ir} \cdot \frac{\partial \pi_{ir}}{\partial p_{jr}} \quad \text{and} \quad k_{fir} = \frac{\partial \Pi_{ir}}{\partial w_{fr}} = Y_{ir} \cdot \frac{\partial \pi_{ir}}{\partial w_{fr}} \qquad [5]$$

The variable, price dependent input coefficients, which appear subsequently in the market clearance conditions, are thus:

$$a_{jir}^{x} = \frac{\partial c_{ir}}{\partial p_{jr}} = \frac{\partial \pi_{ir}}{\partial p_{jr}} \quad \text{and} \quad a_{fir}^{k} = \frac{\partial c_{ir}}{\partial w_{fr}} = \frac{\partial \pi_{ir}}{\partial w_{fr}} \qquad [6]$$

The model captures the production of commodities by aggregate, hierarchical (or nested) constant elasticity of substitution (CES) production functions that characterize the technology through substitution possibilities between capital, labor, energy and material (non-energy) intermediate inputs (KLEM). Two types of production functions are employed: those for fossil fuels (in our case *v* = COL, CRU, GAS) and those for non-fossil fuels (in our case *n* = EIS, ELE, OIL, ROI).

Figure A.1 illustrates the nesting structure in non-fossil fuel production. In the production of non-fossil fuels *nr*, non-energy intermediate inputs *M* (used in fixed coefficients among themselves) are employed in (Leontief) fixed proportions with an aggregate of capital, labor and energy at the top level. At the second level, a CES function describes the substitution possibilities between the aggregate energy input *E* and the value-added aggregate *KL* (For the sake of simplicity, the symbols α, β, ϕ and θ are used throughout the model description to denote the technology coefficients.):

$$Y_{nr} = \min\left\{ (1-\theta_{nr}) M_{nr}, \theta_{nr}\phi_{nr}\left[\alpha_{nr} E_{nr}^{\rho^{KLE}} + \beta_{nr} KL_{nr}^{\rho^{KLE}}\right]^{1/\rho^{KLE}} \right\} \qquad [7]$$

with $\sigma^{KLE} = 1/(1-\rho^{KLE})$ the elasticity of substitution between energy and the primary factor aggregate and θ the input (Leontief) coefficient. Finally, at the third level, capital and labor factor inputs trade-off with a constant elasticity of substitution σ^{KL}:

$$KL_{nr} = \phi_{nr}\left[\alpha_{nr} K_{nr}^{\rho^{KL}} + \beta_{nr} L_{nr}^{\rho^{KL}}\right]^{1/\rho^{KL}} \qquad [8]$$

As to the formation of the energy aggregate *E*, we employ several levels of nesting to represent differences in substitution possibilities between primary fossil fuel types as well as substitution between the primary fossil fuel composite and secondary energy, i.e. electricity. The energy aggregate is a CES composite of electricity and primary energy inputs *FF* with elasticity $\sigma^E = 1/(1-\rho^E)$ at the top nest:

$$E_{nr} = \phi_{nr}\left[\alpha_{nr} ELE_{nr}^{\rho^E} + \beta_{nr} FF_{nr}^{\rho^E}\right]^{1/\rho^E} \qquad [9]$$

The primary energy composite is defined as a CES function of coal and the composite of refined oil and natural gas with elasticity $\sigma^{COA} = 1/(1-\rho^{COA})$. The oil-gas composite is assumed to have a simple Cobb-Douglas functional form with value shares given by θ:

$$FF_{nr} = \phi_{nr}\left[\alpha_{nr} COA_{nr}^{\rho^{COA}} + \beta_{nr}\left(OIL^{\theta_{nr}} \cdot GAS^{1-\theta_{nr}}\right)^{\rho^{COA}}\right]^{1/\rho^{COA}} \qquad [10]$$

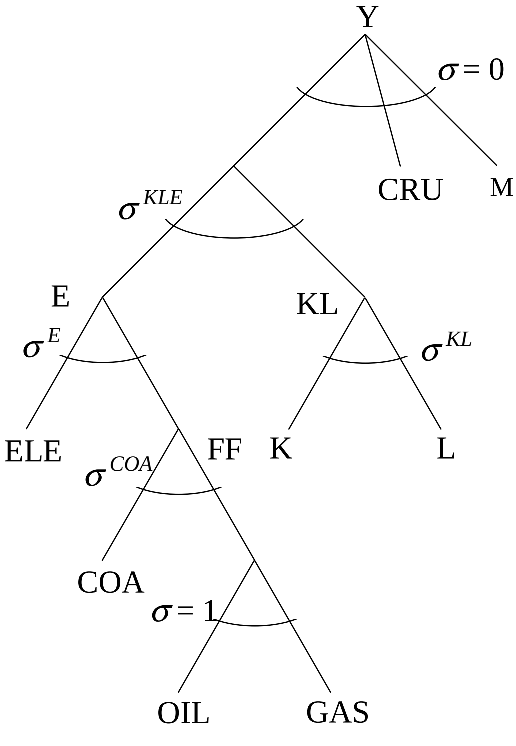

Figure A.1: Nesting structure of non-fossil fuel production

Fossil fuel resources *v* are modeled as graded resources. The structure of production of fossil fuels is given in Figure A.2. It is characterized by the presence of a fossil fuel resource in fixed supply. All inputs, except for the sector-specific resource R, are aggregated in fixed proportions at the lower nest. Mine managers minimize production costs subject to the technology constraint:

$$Y_{vr} = \phi_{vr}\left[\alpha_{vr} R_{vr}^{\rho_v^f} + \beta_{vr}\left[\min\left(\theta_{vr}^{K} K_{vr}, \theta_{vr}^{L} L_{vr}, \theta_{vr}^{E} E_{vr}, \theta_{vr}^{M} M_{jvr}\right)\right]^{\rho_v^f}\right]^{1/\rho_v^f} \qquad [11]$$

The resource grade structure is reflected by the elasticity of substitution between the fossil fuel resource and the capital-labor-energy-material aggregate in production. The substitution elasticity between the specific factor and the Leontief composite at the top level is $\sigma_{vr}^{f} = 1/(1-\rho_{vr}^{f})$. This substitution elasticity is calibrated in consistency with an exogenously given supply elasticity of fossil fuel ε_{vr} according to

$$\varepsilon_{vr} = \frac{1-\gamma_{vr}}{\gamma_{vr}}\sigma_{vr}^{f} \qquad [12]$$

with γvr the resource value share.

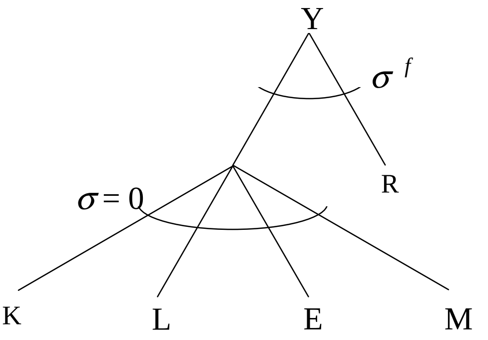

Figure A.2: Nesting structure for fossil fuel production

We now turn to the derivation of the factor demand functions for the nested CES production functions, taking into account the duality between the production function and the cost function The total cost function that reflects the same production technology as the CES production function for e.g. value added *KL* in non-fossil fuel production given by [8] is:

$$C_{nr}^{KL} = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} \cdot KL_{nr} \qquad [13]$$

where PK and PL are the per-unit factor costs for the industry including factor taxes if applicable. The price function for the value-added aggregate at the third level is:

$$PKL_{nr} = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} = c_{nr}^{KL} \qquad [14]$$

Shepard's Lemma gives the price-dependent composition of the value-added aggregate as:

$$\frac{K_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\alpha_{nr}\cdot\frac{PKL_{nr}}{PK_{nr}}\right)^{\sigma^{KL}} , \quad \frac{L_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\beta_{nr}\cdot\frac{PKL_{nr}}{PL_{nr}}\right)^{\sigma^{KL}} \qquad [15]$$

In order to determine the variable input coefficient for capital and labor $a_{nr}{}^{K} = K_{nr} / Y_{nr}$ and $a_{nr}{}^{L} = L_{nr} / Y_{nr}$, one has to multiply [15] with the per unit demand for the value added aggregate KL_{nr} / Y_{nr}, which can be derived in an analogous manner. The cost function associated with the production function [7] is:

$$PY_{nr} = \left(1-\theta_{nr}\right)PM_{nr} + \frac{\theta_{nr}}{\hat{\phi}_{nr}}\left[\hat{\alpha}_{nr}^{\sigma^{KLE}} PE_{nr}^{1-\sigma^{KLE}} + \hat{\beta}_{nr}^{\sigma^{KLE}} PKL_{nr}^{1-\sigma^{KLE}}\right]^{\frac{1}{1-\sigma^{KLE}}} \qquad [16]$$

and

$$\frac{KL_{nr}}{Y_{nr}} = \theta_{nr}\,\hat{\phi}_{nr}^{\sigma^{KLE}-1}\left(\hat{\beta}_{nr}\cdot\frac{PY_{nr}}{PKL_{nr}}\right)^{\sigma^{KLE}} \qquad [17]$$

with θ_{nr} the *KLE* value share in total production. The variable input coefficient for e.g. labor is then:

$$a_{nr}^{L} = \theta_{nr}\,\phi_{nr}^{\sigma^{KL}-1}\,\hat{\phi}_{nr}^{\sigma^{KLE}-1}\left(\beta_{nr}\cdot\frac{PKL_{nr}}{PL_{nr}}\right)^{\sigma^{KL}}\left(\hat{\beta}_{nr}\cdot\frac{PY_{nr}}{PKL_{nr}}\right)^{\sigma^{KLE}} \qquad [18]$$

A.2 Households

In each region, private demand for goods and services is derived from utility maximization of a representative household subject to a budget constraint given by the income level *INC*. The agent is endowed with the supplies of the primary factors of production (natural resources used for fossil fuel production, labor and capital) and tax revenues. In our comparative-static framework, overall investment demand is fixed at the reference level. The household's problem is then:

$$\underset{d_{ir}}{Max}\; W_r\left(d_{ir}\right) \quad s.t.\;\; INC_r = \sum_f w_{fr}\,\bar{k}_{fr} + TR_r = \sum_i p_{ir} d_{ir} \qquad [19]$$

where *W* is the welfare of the representative household in region *r*, *d* denotes the final demand for commodities, $\bar{k}$ is the aggregate factor endowment of the representative agent and *TR* are total tax revenues. Household preferences are characterized by a CES utility function. As in production, the maximization problem in [1] can thus be expressed in form of an unit expenditure function *e* or welfare price index *pw*, given by:

$$pw_r = e_r\left(p_{ir}\right) \qquad [20]$$

Compensated final demand functions are derived from Roy's Identity as:

$$d_{ir} = \overline{INC}_r \frac{\partial e_r}{\partial p_{ir}} \qquad [21]$$

with $\overline{INC}$ the initial level of expenditures.

In the model, welfare of the representative agent is represented as a CES composite of a fossil fuel aggregate and a non-fossil fuel consumption bundle. Substitution patterns within the latter are reflected via a Cobb-Douglas function. The fossil fuel aggregate in final demand consists of the various fossil fuels (*fe* = COL, OIL, GAS) trading off at a constant elasticity of substitution. The CES utility function is:

$$U_r = \left[\alpha_r \left(\sum_{fe} \beta_{fe,r} C_{fe,r}^{\rho^F}\right)^{\rho^C / \rho^F} + \phi_r \left(\prod_{j \notin fe} C_{jr}^{\theta_j}\right)^{\rho^C}\right]^{1/\rho^C} \qquad [22]$$

where the elasticity of substitution between energy and non-energy composites is given by $\sigma_C = 1/(1-\rho_C)$, the elasticity of substitution within the fossil fuel aggregate by $\sigma_{FE} = 1/(1-\rho_{FE})$, and θ_j are the value shares in non-fossil fuel consumption. The structure of final demand is presented in Figure A.3.

Total income of the representative agent consists of factor income, revenues from taxes levied on output, intermediate inputs, exports and imports, final demand as well as tax revenues from CO_2 taxes (TR) and a baseline exogenous capital flow representing the balance of payment deficits B less expenses for exogenous total investment demand $PI \cdot I$. The government activity is financed through lump-sum levies. It does not enter the utility function and is hence exogenous in the model. The budget constraint is then given by:

$$PC_r \cdot C_r = PL_r \cdot \overline{L}_r + PK_r \cdot \overline{K}_r + \sum_v PR_{vr} \cdot \overline{R}_{vr} + TR_r + \overline{B}_r - PI_r \cdot I_r \qquad [23]$$

with C the aggregate household consumption in region r and PC its associated price.

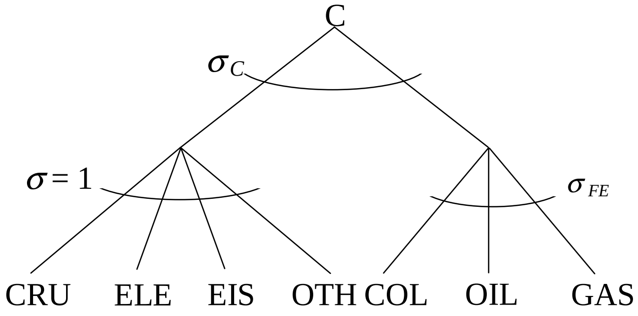

Figure A.3: Structure of household demand

A.3 Foreign Trade

All commodities are traded in world markets and characterized by product differentiation. There is imperfect transformability (between exports and domestic sales of domestic output) and imperfect substitutability (between imports and domestically sold domestic output). Bilateral trade flows are subject to export taxes, tariffs and transportation costs and calibrated to the base year 1995. There is an imposed balance of payment constraint to ensure trade balance, which is warranted through flexible exchange rates, incorporating the benchmark trade deficit or surplus for each region.

On the output side, two types of differentiated goods are produced as joint products for sale in the domestic markets and the export markets, respectively. The allocation of output between domestic sales D and international sales X is characterized by a constant elasticity of transformation (CET) function. Hence, firms maximize profits subject to the constraint:

$$Y_{ir} = \phi_{ir}\left[\alpha_{ir} D_{ir}^{\eta} + \beta_{ir} X_{ir}^{\eta}\right]^{1/\eta} \qquad [24]$$

with $\sigma^{tr} = 1/(1+\eta)$ the transformation elasticity.

Regarding imports, the standard Armington convention is adopted in the sense that imported and domestically produced goods of the same kind are treated as incomplete substitutes (i. e. wine from France is different from Italian wine). The aggregate amount of each (Armington) good A is divided among imports and domestic production:

$$A_{ir} = \phi_{ir}\left[\alpha_{ir} D_{ir}^{\rho^D} + \beta_{ir} M_{ir}^{\rho^D}\right]^{1/\rho^D} \qquad [25]$$

In this expression $\sigma^D = 1/(1-\rho^D)$ is the Armington elasticity between domestic and imported varieties. Imports M are allocated among import regions s according to a CES function:

$$M_{ir} = \phi_{ir}\left[\sum_s \alpha_{ir} X_{isr}^{\rho^M}\right]^{1/\rho^M} \qquad [26]$$

with X the amount of exports from region s to region r and $\sigma^M = 1/(1-\rho^M)$ the Armington elasticity among imported varieties. Intermediate as well as final demands are, hence, (nested CES) Armington composites of domestic and imported varieties.

The assumption of product differentiation permits the model to match bilateral trade with cross-hauling of trade and avoids unrealistically strong specialization effects in response to exogenous changes in trade (tax) policy.

A.4 Carbon emissions

Carbon emissions are associated with fossil fuel consumption in production, investment, government and private demand. Each unit of a fuel emits a known amount of carbon where different fuels have different carbon intensities. The applied carbon coefficients are 25 MT carbon per EJ for coal, 14 MT carbon per EJ for gas and 20 MT carbon per EJ for refined oil.

Carbon policies are introduced via an additional constraint that holds carbon emissions to a specified limit. The solution of the model gives a shadow value on carbon associated with this carbon constraint. This dual variable or shadow price can be interpreted as the price of carbon permits in a carbon permit system or as the CO_2 tax that would induce the carbon constraint in the model. The shadow value of the carbon constraint equals the marginal cost of reduction. It indicates the incremental cost of reducing carbon at the carbon constraint. The total costs represent the resource cost or dead-weight loss to the economy of imposing carbon constraints. Carbon emission constraints induce substitution of fossil fuels with less expensive energy sources (fuel switching) or employment of less energy-intensive manufacturing and production techniques (energy savings). The only means of abatement are hence inter-fuel and fuel-/non-fuel substitution or the reduction of intermediate and final consumption.

Given an emission constraint producers as well as consumers must pay this price on the emissions resulting from the production and consumption processes. Revenues coming from the imposition of the carbon constraint are given to the representative agent. The total cost of Armington inputs in production and consumption that reflects the CES production technology in [25] but takes CO2 emission restrictions into account is:

$$C_{ir}^{A} = \left[\left(\alpha_{ir}^{\sigma^D} PD_{ir}^{1-\sigma^D} + \beta_{ir}^{\sigma^A} PM_{ir}^{1-\sigma^D} \right)^{1/\left(1-\sigma^D\right)} + \tau_r \cdot a_i \right] \cdot A_{ir} \qquad [27]$$

with a_i the carbon emissions coefficient for fossil fuel i and τ the shadow price of CO_2 in region r associated with the carbon emission restriction:

$$\overline{CO2}_r = \sum_i A_{ir} \cdot a_i \qquad [28]$$

where $\overline{CO2}_r$ is the endowment of carbon emission rights in region r.

A.5 Zero Profit and Market Clearance Conditions

The equilibrium conditions in the model are zero profit and market clearance conditions. Zero profit conditions as derived in [2] require that no producer earns an “excess” profit in equilibrium. The value of inputs per unit activity must be equal to the value of outputs. The zero profit conditions for production, using the variable input coefficient derived above, is:

$$PK \cdot a_{ir}^{K} \cdot Y_{ir} + PL \cdot a_{ir}^{L} \cdot Y_{ir} + \sum_j PA_j \cdot a_{jir}^{M} \cdot Y_{ir} = PY_{ir} \cdot Y_{ir}\,. \qquad [29]$$

The market clearance conditions state that market demand equals market supply for all inputs and outputs. Market clearance conditions have to hold in equilibrium. Domestic markets clear, equating aggregate domestic output plus imports, i.e. total Armington good supply, to aggregate demand, which consists of intermediate demand, final demand, investment and government demand:

$$A_{ir} = \sum_j Y_{jr} \frac{\partial \pi_{jr}^{Y}}{\partial PA_{ir}} + C_r \frac{\partial e_r}{\partial PA_{ir}} \qquad [30]$$

with *PA* the price of the Armington composite. $\pi_{ir}{}^{Z}$ is the per unit zero profit function with *Z* the name assigned to the associated production activity. The derivation of $\pi_{ir}{}^{Z}$, with respect to input and output prices, yields the compensated demand and supply coefficients, e.g. $\partial\, \pi_{jr}{}^{Y} \,/\, \partial\, PA_{ir} = a_{ijr}{}^{A}$ the intermediate demand for Armington good *i* in sector *j* of region *r* per unit of output *Y*. Output for the domestic market equals total domestic demand:

$$Y_{ir} \frac{\partial \pi_{ir}^{Y}}{\partial PD_{ir}} = \sum_j A_{jr} \frac{\partial \pi_{jr}^{A}}{\partial PD_{ir}} \qquad [31]$$

with *PD* the domestic commodity price. Export supply equals import demand across all trading partners:

$$Y_{ir} \frac{\partial \pi_{ir}^{Y}}{\partial PX_{ir}} = \sum_s M_{is} \frac{\partial \pi_{is}^{M}}{\partial PX_{ir}} \qquad [32]$$

with *PX* the export price. Aggregate import supply equals total import demand:

$$M_{ir} = A_{ir} \frac{\partial \pi_{ir}^{A}}{\partial PM_{ir}} \qquad [33]$$

where *PM* is the import price.

Primary factor endowment equals primary factor demand:

$$\overline{L}_r = \sum_i Y_{ir} \frac{\partial \pi_{ir}^{Y}}{\partial PL_r}, \qquad [34]$$

$$\overline{K}_r = \sum_i Y_{ir} \frac{\partial \pi_{ir}^{Y}}{\partial PK_r}, \qquad [35]$$

$$\overline{R}_{vr} = Y_{vr} \frac{\partial \pi_{vr}^{Y}}{\partial PR_{vr}}. \qquad [36]$$

An equilibrium is characterized by a set of prices in the different goods and factor markets such that the zero profit and market clearance conditions stated above hold.

A.6 International Permit Trade and Monopolistic Permit Supply

Under competitive permit trading, all countries can import or export CO_2 permits considering the international permit price as exogenous. The zero-profit condition for export activities of country *r* is given as weak inequality:

$$\Pi_r^{CEXP} = P - \tau_r \leq 0. \qquad [37]$$

where *P* is the international permit price, τ_r reflects the domestic carbon price (see [28]) and $CEXP_r$ is the associated dual variable, which indicates the activity level of CO_2 exports from region *r* . Likewise, the zero-profit condition for import activities of country *r* is given by:

$$\Pi_r^{CIMP} = \tau_r - P \leq 0. \qquad [38]$$

where $CIMP_r$ is the associated dual variable, which indicates the activity level of CO_2 imports in region *r*.

The market clearance condition for tradable permits is:

$$\sum_r CEXP_r = \sum_r CIMP_r \ . \qquad [39]$$

where *P* - the international permit price - is the associated dual variable.

Monopolistic permit supply is characterized as a situation where one country - in our case FSU - has supply power in the permit market while all other countries behave as price takers. The monopolist sets the permit price as a markup on its marginal abatement costs to maximize profits (with the usual inverse relationship between the markup rate and the price elasticity of permit demand). Given the complexity of functional forms in our CGE framework, it is not possible to derive an algebraic formula for the markup rate. We therefore represent the markup in the model as an export tariff which drives a wedge between the international permit price and the marginal abatement costs in FSU:

$$\Pi_{FSU}^{EXP} = P - \tau_{FSU}(1 + t_{FSU}^{EXP}) \leq 0 \ . \qquad [40]$$

The markup is equivalent to a quota on the sales of permits where the quota rents accrue to FSU. In order to determine the optimal tariff or quota numerically, we raise the tariff of FSU in sufficiently small steps and then identify that rate which maximises its welfare in terms of real consumption *C*.

A.7 Overview of Elasticities

Table A.1 provides a summary of elasticity values adopted for the core simulations.

Table A.1: Default values of key substitution and supply elasticities

	Description	Value
Substitution elasticities in non-fossil fuel production		
σ^{KLE}	Energy vs. value added	0.5
σ^{KL}	Capital vs. labor	1.0
σ^{E}	Electricity vs. primary energy inputs	0.3
σ^{COL}	Coal vs. gas-oil	0.5
Substitution elasticities in final demand		
σ_{C}	Fossil fuels vs. non-fossil fuels	0.8
σ_{FE}	Fossil fuels vs. fossil fuels	0.3
Elasticities in international trade (Armington)		
σ^{D}	Substitution elasticity between the import composite vs. domestic inputs	2.0
σ^{M}	Substitution elasticity between imports from different regions forming the import composite	4.0
σ^{tr}	Transformation elasticity domestic vs. export	4.0
Exogenous supply elasticities of fossil fuels ε		
Crude oil		1.0
Coal		1.0
Natural gas		1.0

For the sensitivity analysis reported in section 3.3, the lower and upper values of the uniform probability distributions for six key elasticities are as follows: $1 < \sigma^{D} < 4$; $2 < \sigma^{M} < 8$; $0.25 < \sigma^{KLE} < 0.75$; $0.6 < \sigma^{C} < 1$; $0.25 < \varepsilon_{CRU} < 1$; $0.25 < \varepsilon_{COL} < 1$.

Appendix B: Benchmark Data - Regional and Sectoral Aggregation

The model is built on a comprehensive energy-economy dataset that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flow. The underlying data base is GTAP-EG (version 5) which reconciles the most recent GTAP economic production and trade dataset for the year 1997 with OECD/IEA energy statistics for 50 regions and 23 sectors (Rutherford and Paltsev 2000). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Sectors and regions of the original GTAP-EG data set are aggregated according to Tables B.1 and B.2 to yield the model's sectors and regions.

Table B.1: Sectoral aggregation

Sectors in GTAP-EG			
AGR	Agricultural products	NFM	Non-ferrous metals
CNS	Construction	NMM	Non-metallic minerals
COL	Coal	OIL	Refined oil products
CRP	Chemical industry	OME	Other machinery
CRU	Crude oil	OMF	Other manufacturing
DWE	Dwellings	OMN	Mining
ELE	Electricity and heat	PPP	Paper-pulp-print
FPR	Food products	SER	Commercial and public services
GAS	Natural gas works	T_T	Trade margins
I_S	Iron and steel industry	TRN	Transport equipment
LUM	Wood and wood-products	TWL	Textiles-wearing apparel-leather

Mapping from GTAP-EG sectors to model sectors as of Table 1		
	Energy	
COL	Coal	COL
CRU	Crude oil	CRU
GAS	Natural gas	GAS
OIL	Refined oil products	OIL
ELE	Electricity	ELE
	Non-Energy	
EIS	Energy-intensive sectors	CRP, I_S, NFM, NMM, PPP, TRN
ROI	Rest of industry	AGR, CNS, DWE, FPR, LUM, OME, OMF, OMN, SER, T_T, TWL

Table B.2: Regional aggregation

Regions in GTAP-EG			
ARG	Argentina	MYS	Malaysia
AUS	Australia	NZL	New Zealand
BRA	Brazil	PHL	Philippines
CAM	Central America and Caribbean	RAP	Rest of Andean Pact
CAN	Canada	RAS	Rest of South Asia
CEA	Central European Associates	REU	Rest of EU
CHL	Chile	RME	Rest of Middle East
CHN	China	RNF	Rest of North Africa
COL	Columbia	ROW	Rest of World
DEU	Germany	RSA	Rest of South Africa
DNK	Denmark	RSM	Rest of South America
EFT	European Free Trade Area	RSS	Rest of South-Saharan Africa
FIN	Finland	SAF	South Africa
FSU	Former Soviet Union	SGP	Singapore
GBR	United Kingdom	SWE	Sweden
HKG	Hong Kong	THA	Thailand
IDN	Indonesia	TUR	Turkey
IND	India	TWN	Taiwan
JPN	Japan	URY	Uruguay
KOR	Republic of Korea	USA	United States of America
LKA	Sri Lanka	VEN	Venezuela
MAR	Morocco	VNM	Vietnam
MEX	Mexico		

Mapping from GTAP-EG regions to model regions as of Table 1		
	Annex B	
USA	United States	USA
EUR	OECD Europe (incl. EFTA)	DEU, DNK, EFT, FIN, GBR, REU, SWE
JPN	Japan	JPN
CAN	Canada	CAN
AUN	Australia, New Zealand	AUS, NZL
CEA	Central and Eastern Europe	CEA
FSU	Former Soviet Union	FSU
	Non-Annex B	
ROW	Rest of the World	KOR, LKA, MYS, PHL, RAS, SGP, THA, TWN, VNM, IDN, MEX, RME, RNF, VEN, MAR, ROW, RSA, RSS, SAF, TUR

Appendix C: Baseline Projections - Forward Calibration

The magnitude and distribution of abatement costs associated with the implementation of the Kyoto emission constraints crucially depend on the business-as-usual (*BaU*) projections for GDP, fuel prices, energy efficiency improvements, etc. In our comparative-static framework, we infer the *BaU* economic structure of the model's regions for the year 2010 using most recent projections by the U.S. Department of Energy (IEO 2001) for GDP growth, fossil fuel production, and future energy prices. We incorporate autonomous energy efficiency improvement factors which scale energy demand functions to match the exogenous IEO emission forecasts. The concrete forward calibration of the model entails three steps.

First, we fix the time profile of fossil fuel supplies from the model's regions to the exogenous baseline projections by making supplies inelastic and scaling sector-specific resources with the exogenous growth rates in fossil fuel production. This allows us to partially control the emission profile from the supply side. Within the *BaU* calculation, we endogenously adjust the resource endowments of fossil fuels to calibrate the model to given exogenous target prices for fossil fuels. At the same time we incorporate exogenous, region-specific GDP growth rates to scale the labor and capital stock of our static model.

Second, we incorporate exogenous autonomous energy efficiency improvements (AEEI) to match the exogenous carbon emission profiles as provided by IEO. The AEEI reflects the rate of change in energy intensity, i.e. the ratio of energy consumption over gross domestic product, holding energy prices constant. It is a measure of all non-price induced changes in gross energy intensity including technical developments that increase energy efficiency as well as structural changes.

Third, we recalibrate fossil fuel supply functions locally to exogenous estimates of supply elasticities. The last step assures empirical reaction of fossil fuel production to policy induced changes in world energy prices of fuels.

To account for the importance of exogenous baseline projections, the model can be calibrated to alternative data sources in an automated way. In the current set-up, one can perform sensitivity analysis with respect to the three different core scenarios of IEO: low economic growth, reference case, and high economic growth.

Appendix D: GHG Emission Reduction Targets for Annex-B countries

	Label[a]	Original Kyoto Targets (*OLD*)[b] (% of 1990 base year GHG emissions)	Revised Targets (*NEW*)[c] (% of 1990 base year GHG emissions)
Australia	AUN	108	110.7
Austria	EUR	87	92.9
Belgium	EUR	92.5	93.8
Bulgaria	CEA	92	95.2
Canada	CAN	94	107.9
Croatia	CEA	95	95
Czech Republic	CEA	92	94.1
Denmark	EUR	79	81.1
Estonia	FSU	92	94.7
Finland	EUR	100	107.8
France	EUR	100	103.9
Germany	EUR	79	80.7
Greece	EUR	125	133.1
Hungary	CEA	94	97.8
Iceland	EUR	110	118
Ireland	EUR	113	116.2
Italy	EUR	93.5	95.3
Japan	JPN	94	99.2
Latvia	FSU	92	98
Liechtenstein	EUR	92	107.9
Lithuania	EUR	92	96.5
Luxemburg	EUR	72	79.6
Monaco	EUR	92	93
Netherlands	EUR	94	95.2
New Zealand	AUN	100	107
Norway	EUR	101	105.3
Poland	CEA	94	96.5
Portugal	EUR	127	130.7
Romania	CEA	92	96.2
Russian Federation	FSU	100	105.7
Slovakia	CEA	92	96.3
Slovenia	CEA	92	100.4
Spain	EUR	115	118.9
Sweden	EUR	104	109.5
Switzerland	EUR	92	96.6
Ukraine	FSU	100	102.4
United Kingdom	EUR	87.5	88.8
United States	USA	93	96.8

[a] Label of aggregate model region which includes the respective Annex B country

[b] UNFCCC (1997)

[c] Estimates by the European Commission accounting for sink credits as agreed in Bonn and Marrakesh (Nemry 2001)