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Economic and environmental impacts of the Kyoto Protocol

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Abstract. In 2003 the Kyoto Protocol, which imposes legally binding greenhouse gas emission constraints on industrialized countries, is likely to enter into force. The Protocol has been celebrated as a milestone in climate protection, but standard economic theory casts doubt that it will go beyond symbolic policy. In this paper, we show that the final concretion of the Kyoto Protocol is consistent with the theoretical prediction: Kyoto more or less boils down to business-as-usual without significant compliance costs to ratifying parties. JEL Classification: D58, Q43, Q58

Conséquences économiques et environnementales du protocole de Kyoto. En 2003, le protocole de Kyoto, qui impose aux pays industrialisés l'obligation de réduire leurs émissions de gaz à effet de serre, entrera probablement en vigueur. Si le protocole a été accueilli comme un grand pas en avant dans le combat pour protéger l'environnement, la théorie économique jette un regard sceptique sur la portée réelle d'un tel accord et le considère comme un geste symbolique. Dans ce mémoire, on montre que la concrétisation finale de l'accord de Kyoto s'arrime aux prédictions théoriques : Kyoto n'est rien de plus que « business-as-usual » et n'impliquera pas de coûts significatifs pour les parties qui ont signé le protocole.

1. Introduction

In 2003 the first legally binding international agreement on climate protection is likely to enter into force. 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 (GHG) by roughly 5% on average, compared with their 1990 emission levels, during the commitment period from 2008 to 2012 (UNFCCC 1997). The

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so-called Kyoto Protocol has been celebrated as a breakthrough in international climate policy, because it implied – in its original form – substantial emission reductions for 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, since climate protection constitutes the case of voluntarily providing a pure global public good. 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 arise only in the far distant future.

In this paper, we investigate whether the final concretion of the Kyoto Protocol is consistent with the theoretical prediction. A first back-of-the-envelope analysis shows indeed that recent changes to the Kyoto Protocol – most notably, U.S. withdrawal and unrestricted emissions trading – boil down climate policy to business as usual without any compliance costs for participating countries. At second glance, however, it appears that market power on emission markets may turn the Kyoto Protocol into an agreement with binding emission constraints. Since the induced effects on regional welfare and global emissions are not directly observable, we use an established computable general equilibrium (CGE) model of global trade and energy use for impact analysis. The quantitative CGE results back the proposition of standard economic theory, because compliance costs as well as environmental effects 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, Carraro, and Cersosimo 2001 for a synopsis). However, none of the studies links quantitative results to the prediction of standard economic theory. Furthermore, our quantitative analysis combines central features of an appropriated impact assessment such as market power in permit trade or terms-of-trade effects, and it proves robustness of conclusions with respect to a wide range of uncertainties in the model parameterization space.

2. The Kyoto Protocol at first view: what theory predicts

Climate protection poses the problem of providing a global public good. In the absence of any supranational authority, countries behave non-cooperatively, that is, each country decides on its GHG abatement according to a comparison of its own benefits from abatement and its own costs of abatement. For concreteness, 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 $B_i = B_i(Q)$, while costs depend on the national abatement level that a single country chooses: $C_i = C_i(q_i)$. In a non-cooperative Nash equilibrium, countries choose abatement levels that equate their own marginal benefits from abatement and their own marginal abatement costs, that is, $B'_i = C'_i$. 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.¹ 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.²

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. Although the non-cooperative solution in general implies positive contributions to the provision of the public good, we assume the optimal abatement level q_i and, thus, compliance costs to be (close to) zero. Apart from the classical free-rider incentive, the main reason is that with respect to 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. Any rational government, therefore, will not enter an international agreement which is likely to impose significant costs.

Prima facie, the effective outcome of the Kyoto Protocol – after five years of negotiation – backs our simple theoretical argument. Table 1 provides the quantitative evidence.

Column 'Baseline Emissions – 1990' of table 1 lists the historic emissions for all annex B regions, and column 'Nominal Reduction – OLD' provides the reduction targets as originally foreseen by the Kyoto Protocol. For example, Canada (CAN) has committed itself to reduce its GHG emissions by 6.0% compared with 1990 emission levels. Since these targets will not become legally binding before the Kyoto commitment period (2008–12), the appropriate reference for the *effective* targets are the business-as-usual (*BaU*) emissions during the commitment period that are reported for the central year 2010 in column 'Baseline Emissions – 2010.' Except for the economies in transition, which include Central and Eastern Europe (CEA) as well as the Former Soviet Union (FSU), the Kyoto targets translate into much more stringent *effective* targets, because

1 Simulation studies that focus on *long-term* cumulative emission reduction targets and identify *optimal* abatement paths typically assume a global planner, neglecting the incentive problem of international cooperation (see e.g. Nordhaus 1993 or Manne and Richels 1995).

2 Clearly, the purpose of climate negotiations is to achieve co-operative solutions which improve upon the outcome in the absence of any international agreement. Note, however, that the incentive for countries to free ride on the contributions of other countries remains even if such an agreement exists, since there is no supranational authority, that could coerce co-operative behavior by credible sanctions.

TABLE 1
Baseline emissions and targets*

Region	Baseline Emissions (MtC) ^a		Kyoto Targets (% wrt 1990) ^b		Effective Targets (% wrt 2010)		Effective Targets (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 USA 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 USA in ^d	4097	4416	-5.0	-0.5	-11.9	-7.7	-525	-339

* For reasons of data availability, we apply the GHG reduction targets to CO₂ only, which is by far the most important GHG among industrialized countries.

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 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

industrialized countries are projected to have economic growth accompanied by a considerable increase in GHG emissions from fossil fuel combustion. 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. As will be elaborated below, the availability of these excess emissions, which are referred to as ‘hot air’ will crucially affect the potential compliance costs of OECD countries under the Kyoto Protocol.

An assessment of table 1 with respect to the implementation of the Kyoto Protocol in its original form, that is, 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, aggregate Annex B emissions are supposed to fall by roughly 12% compared with *BaU* (see intersection of row ‘Total USA in’ with column ‘Effective Targets – *OLD*’).

More recently, however, there have been major modifications to the Kyoto Protocol. 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. U.S. withdrawal had a crucial impact on the climate policy negotiations at Bonn (June 2001) and Marrakech (October

2001). Owing to the ‘double trigger’ mechanism,³ entry into force of the Kyoto Protocol is no longer possible without participation of FSU and the 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 sinks⁴ (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 row ‘Total USA out’ illustrates the dramatic implications of U.S. withdrawal and unrestricted permit trade. The total amount of hot air exceeds the cumulative cutback requirements across remaining Annex B countries. Without rationing of hot air, the Kyoto Protocol boils down to business as usual confirming the proposition of standard economic theory.

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

A more realistic assessment of market mechanisms, however, warrants caution against our simple back-of-the-envelope calculation. Obviously, FSU as the dominant supplier of emission rights (due to large entitlements with hot air) may act as a monopolist, reducing its permit supply and charging a mark-up over its marginal abatement costs (which are zero for hot air) to maximize profits. The international permit price will be positive, imposing non-zero compliance costs on industrialized countries with emission cutback requirements.

Our main interest, then, is to assess how much the implied costs for major Annex B parties differ from zero when market power is taken into account. In order to obtain such cost estimates, we make use of a standard CGE model of world trade and energy use (Böhringer 2002; Böhringer and Rutherford 2002).⁵ In the basic model version (see the appendix for the algebraic model summary),

3 On the one side, at least 55 countries have to ratify the treaty through their national parliaments. On the other side, those countries that ratify the treaty have to account for at least 55% of the CO₂ emissions in 1990 (the Protocol’s base year).

4 Credits are composed of sinks from forest management and agricultural activities that store CO₂. Given that these activities largely coincide with business as usual, we assume that there are no costs to earning the credits (see Nemry 2001) that relax the cutback requirements for energy-related emissions.

5 The data and model to replicate all of our results can be obtained from the authors upon request. The aggregated regions of the model underlying our analysis are listed in table 1. The aggregated sectors include energy sectors (coal (COL), crude oil (CRU), natural gas (GAS), refined oil products (OIL), and electricity (ELE)), a composite of energy intensive sectors (EIS), and the rest of industry (ROI). Details on the mapping of the original GTAP-EG regions and sectors to the model’s regions and sectors are available as a download from ftp://ftp.zew.de/pub/zew-docs/div/cje_kyoto.pdf. This download also provides a graphical exposition of functional forms (Appendix B of the download), details on the model’s forward calibration (Appendix C of the download), as well as on the assignment of emission reduction targets (Appendix E of the download).

all factor and commodity markets are assumed to be competitive.⁶ For our simulations, we drop this assumption with respect to emissions trading and treat FSU as a monopoly supplier of emission permits. Profit-maximizing behaviour then entails the equalization of marginal abatement cost and perceived marginal revenue, which implies that the permit price set by FSU is a mark-up on marginal cost. Obviously, the mark-up 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.

As is customary in applied general equilibrium analysis, the model is based on economic transactions in a particular benchmark year (1995 in our case). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities (see table A6). As to benchmark quantities and prices, we employ the GTAP-EG database (see Rutherford and Paltsev 2000), which provides a consistent representation of energy markets in physical units and detailed accounts of regional production and consumption as well as bilateral trade, including all types of (indirect) taxes.

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, and so on. In our comparative-static framework, we infer the *BaU* economic structure of the model's regions for the year 2010 using projections of the most recent 'International Energy Outlook' (IEO 2001) by the U.S. Department of Energy 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. 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 history of negotiations on the concrete implementation of the Kyoto Protocol along three key dimensions: fully domestic action (*NTR*) versus Annex B emissions trading (*TRD*), U.S. compliance (*in*) versus U.S. withdrawal (*out*), and Kyoto targets without sink credits (*OLD*) versus Kyoto targets updated with sink credits (*NEW*).

6 Supplies of primary factors are exogenous in the central model version. Model variants that incorporate elastic labour supply and savings demand (see for an analytical representation <http://www.gams.com/solvers/mpsge/cesfun.htm#gemtap>) do not change our qualitative results.

TABLE 2
Economic and environmental impacts of implementing the Kyoto Protocol

	<i>NTR_in_OLD</i>	<i>NTR_out_OLD</i>	<i>NTR_out_NEW</i>	<i>TRD_out_NEW</i>
Consumption change in % vs. <i>BaU</i>				
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. <i>BaU</i>				
TOTAL	9.6	2.8	2.3	0.7
Leakage in %*				
TOTAL	14	30	30	9

*Ratio of emission change in non-abating regions over aggregate emission reduction in abating regions

Scenario *NTR_in_OLD* considers the implementation of the Kyoto Protocol in its initial form with fully domestic action (*NTR*), that is, no trade in emission rights, U.S. compliance (*in*) for the Kyoto reduction targets without sink credits (*OLD*). We see that emission constraints as originally mandated under the Kyoto Protocol induce non-negligible adjustment costs to OECD countries for the case of fully domestic action.

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. 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. 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 net fuel exporters such as FSU or ROW are negatively affected.⁷ 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 scenario *NTR_out_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.

Scenario *NTR_out_NEW* reflects a situation without international permit trade (*NTR*) and without U.S. compliance (*out*), where the Kyoto targets are updated with sink credits (*NEW*): Sink credits considerably reduce compliance costs, but the effective burden is still significant (with up to 90 USD per capita for AUN) if regions must meet their targets through domestic action only.

The drastic drop in costs for OECD countries comes from unrestricted annex B emissions trading together with U.S. withdrawal, as captured in scenario *TRD_out_NEW*, which characterizes the final agreement on the Kyoto implementation after the climate policy negotiations in Bonn and Marrakech. Although compliance costs for OECD countries are still different from zero, owing to monopolistic permit pricing by FSU, comparison of cost figures under the initial Kyoto setting (*NTR_in_OLD*) and its final concretion clearly backs our initial proposition that, after all, Kyoto should come down to symbolic policy.

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 pro-competitive firm-to-firm emissions trading or the Clean Developing Mechanism

⁷ See Böhringer and Rutherford (2002) for a detailed discussion of the sources and magnitude of terms-of-trade effects from carbon abatement.

TABLE 3
Implications of alternative baseline projections (*TRD_out_NEW*)

	<i>LOW</i>	<i>REFERENCE</i>	<i>HIGH</i>
Consumption change in % vs. <i>BaU</i>			
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. <i>BaU</i>			
TOTAL	0.3	0.7	1.0
Leakage in %			
TOTAL	9	9	9

(CDM), which allows the purchase of emission credits from abatement in non-Annex B developing countries.

With the decrease in compliance costs, global environmental effectiveness drops close to zero when we incorporate step by step the changes to the initial Protocol. Except for hot air, U.S. withdrawal, and sink credits, global environmental effectiveness is affected by 'leakage' (see Felder and Rutherford 1993): Sub-global abatement of carbon leads to an increase in emissions in non-abating regions, reducing the global environmental effectiveness. Not

TABLE 4
Results of Monte Carlo Simulation

	TRD_in_NEW					NTR_out_OLD					NTR_out_NEW					TRD_out_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	-0.63	-0.61	-0.60	-0.71	-0.53	-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	-0.50	-0.48	-0.48	-0.54	-0.44	-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	-0.10	-0.10	-0.10	-0.12	-0.08	-0.24	-0.26	-0.26	-0.29	-0.22	-0.19	-0.20	-0.20	-0.20	-0.17	-0.06	-0.06	-0.06	-0.07	-0.05
JPN	-0.26	-0.31	-0.31	-0.38	-0.21	-0.06	-0.08	-0.08	-0.10	-0.05	-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	2.16	2.02	1.98	1.39	2.86	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	2.78	2.80	2.69	2.15	3.72	-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	-0.27	-0.28	-0.27	-0.35	-0.23	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	-0.13	-0.11	-0.11	-0.15	-0.09	-0.19	-0.17	-0.16	-0.23	-0.13	-0.15	-0.14	-0.14	-0.13	-0.11	-0.03	-0.03	-0.03	-0.04	-0.02
TOTAL	-0.24	-0.25	-0.25	-0.31	-0.21	-0.06	-0.06	-0.06	-0.06	-0.05	-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	43	43	42	34	55	123	132	120	89	203	106	113	104	77	172	18	17	17	14	20
CAN	145	154	145	112	222	43	43	42	34	55	132	137	130	99	197	64	65	63	51	87	18	17	17	14	20
EUR	111	114	110	88	149	43	43	42	34	55	106	108	104	83	143	87	88	85	69	115	18	17	17	14	20
JPN	183	191	181	139	270	43	43	42	34	55	176	184	173	133	262	129	133	127	100	183	18	17	17	14	20
CEA	0	0	0	0	0	43	42	42	34	55	0	0	0	0	0	0	0	0	0	0	18	17	17	14	20
FSU	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
USA	156	170	156	114	271	43	43	42	34	55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Consumption change in USD₉₇ per Capita

AUN	-114	-113	-110	-134	-99	-62	-59	-59	-69	-52	-107	-104	-103	-128	-86	-90	-89	-86	-107	-76	-28	-26	-28	-31	-21
CAN	-162	-155	-153	-174	-141	-53	-52	-53	-59	-47	-68	-70	-68	-82	-59	-32	-32	-32	-35	-29	-15	-14	-15	-15	-12

Consumption change in USD₉₇ per Capita

EUR	-23	-25	-26	-31	-18	-13	-13	-14	-16	-10	-31	-33	-34	-38	-29	-24	-26	-26	-29	-22	-8	-8	-8	-8	-7
JPN	-53	-61	-61	-76	-43	-13	-15	-15	-20	-10	-67	-76	-76	-91	-57	-43	-50	-51	-59	-35	-9	-10	-9	-10	-9
CEA	8	8	8	5	12	36	33	33	23	47	4	5	5	2	7	3	4	4	2	6	12	11	11	7	16
FSU	-12	-11	-11	-13	-9	34	34	33	27	46	-9	-8	-8	-10	-6	-7	-7	-6	-8	-5	5	5	4	3	6
USA	-92	-102	-96	-142	-76	-49	-50	-49	-63	-41	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	4.40	4.39	4.40	4.10	4.60	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
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surprisingly, leakage increases with the number of non-abating regions (USA *in* versus USA *out*) and decreases with carbon trade (*NTR* versus *TRD*).

4. Sensitivity analysis

The results of table 2 are based on the reference scenario of the most recent International Energy Outlook (IEO 2001) and common values for key elasticities (see table A6).

Obviously, the effects induced by the implementation of the Kyoto Protocol crucially depend on the business-as-usual (*BaU*) projections for GDP and emissions. Any careful policy assessment thus requires sensitivity analysis with respect to alternative baseline projections. We have performed “piece-meal” sensitivity analysis for two additional baseline projections reported in the International Energy Outlook, where the growth potential of the world economy is considered either more pessimistic (case: *LOW*) or more optimistic (case: *HIGH*), compared with the reference scenario. 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 *TRD_out_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 can draw higher profits from the sales of emission rights.

In order to evaluate the sensitivity of our central model results with respect to uncertainties in the elasticity space, we have conducted 1000 Monte Carlo simulations. In each simulation, values for six elasticities (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 A6). 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.

5. Conclusion

The Kyoto Protocol, which imposes emission reduction targets on industrialized countries, is often celebrated as a milestone in climate protection, but standard economic theory casts doubt that Kyoto will go beyond symbolic policy.

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. Following a simple back-of-the-envelope calculation that backs the theoretical proposition, we have argued that market power in emissions trading might prevent Kyoto from boiling down to purely symbolic policy. However, simulations with a large-scale CGE model of world trade and global energy use show that even for extreme assumptions on market power Kyoto is not much different from business as usual. The residual costs for OECD countries complying with 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. 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: Algebraic model summary

This appendix provides an algebraic summary of the equilibrium conditions for our comparative-static model designed to investigate the economic implications of the Kyoto Protocol in 2010, compared with a business-as-usual economic development in which no GHG emission abatement policies apply. Before presenting the algebraic exposition, we state our main assumptions and introduce the notation.

- Nested separable constant elasticity of substitution (CES) functions characterize the use of inputs in production. All production exhibits non-increasing returns to scale. Goods are produced with capital, labour, energy and material (KLEM).
- A representative agent (RA) in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labour, and capital. The RA maximizes utility from consumption of a CES composite, subject to a budget constraint with fixed demand for investment (i.e., fixed demand for a savings good) and public good provision. The aggregate consumption bundle combines demands for fossil fuels, electricity, and non-energy commodities. Total income of the RA consists of factor income and taxes (including revenues from carbon taxes or carbon permits).
- Supplies of labour, capital, and fossil-fuel resources are exogenous. Labour and capital are mobile within domestic borders but cannot move between regions; natural resources are sector specific.
- All goods are differentiated by region of origin. Constant elasticity of transformation functions (CET) characterize the differentiation of production between production for the domestic markets and the export markets. Regarding imports, nested CES functions characterize the choice between imported and domestic varieties of the same good (Armington).

Two classes of conditions characterize the competitive equilibrium for our model: zero profit conditions and market clearance conditions. The former class determines activity levels and the latter determines price levels. In our algebraic exposition, the notation Π_{jr}^z is used to denote the profit function of sector j in region r , where z is the name assigned to the associated production activity. Differentiating the profit function with respect to input and output prices provides compensated demand and supply coefficients, which appear

subsequently in the market clearance conditions. We use i (aliased with j) as an index for commodities (sectors) and r (aliased with s) as an index for regions. The label EG represents the set of energy goods and the label FF denotes the subset of fossil fuels. Tables A1–A6 explain the notations for variables and parameters employed within our algebraic exposition. Figures A1–A4 provide a graphical exposition of the production and final consumption structure. For the sake of transparency, we do not provide an explicit representation of taxes except for carbon taxes (which can be readily interpreted as the price of carbon permits).

A.1. Zero profit conditions

1. Production of goods except fossil fuels:

$$\begin{aligned} \Pi_{ir}^Y &= \left(\theta_{ir}^X p_{ir}^{X^{1-\eta}} + (1 - \theta_{ir}^X) p_{ir}^{1-\eta} \right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} P_{jr}^A \\ &\quad - \theta_{ir}^{KLE} \left[\theta_{ir}^E p_{ir}^E 1^{-\sigma_{KLE}} + (1 - \theta_{ir}^E) \left(w_r^{\alpha_{jr}^L} v_r^{\alpha_{jr}^K} \right)^{1-\sigma_{KLE}} \right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \quad i \notin FF \end{aligned}$$

2. Production of fossil fuels:

$$\begin{aligned} \Pi_{ir}^Y &= \left(\theta_{ir}^X p_{ir}^{X^{1-\eta}} + (1 - \theta_{ir}^X) p_{ir}^{1-\eta} \right)^{\frac{1}{1-\eta}} \\ &\quad - \left[\theta_{ir}^Q q_{ir}^{1-\sigma_{Q,i}} + (1 - \theta_{ir}^Q) \left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_j \theta_{jir}^{FF} P_{jr}^A \right)^{1-\sigma_{Q,i}} \right]^{\frac{1}{1-\sigma_{Q,i}}} = 0 \\ &= i \in FF \end{aligned}$$

3. Sector-specific energy aggregate:

$$\begin{aligned} E_{ir} &= p_{ir}^E - \left\{ \theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1 - \theta_{ir}^{ELE}) \right. \\ &\quad \left. \left[\theta_{ir}^{COA} p_{\{COA,r\}}^{A^{1-\sigma_{COA}}} + (1 - \theta_{ir}^{COA}) \left(\prod_{j \in LQ} P_{jr}^{A^{\beta_{jr}}} \right)^{1-\sigma_{COA}} \right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}} = 0 \end{aligned}$$

4. Armington aggregate:

$$\Pi_{ir}^A = p_{ir}^A - \left[\left(\theta_{ir}^A p_{ir}^{1-\sigma_A} + (1 - \theta_{ir}^A) p_{ir}^{M^{1-\sigma_A}} \right)^{\frac{1}{1-\sigma_A}} + t_r^{CO2} a_i^{CO2} \right] = 0$$

5. Aggregate imports across import regions:

$$\Pi_{ir}^M = p_{ir}^M - \left(\sum_s \theta_{isr}^M p_{is}^{X^{1-\sigma_M}} \right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

$$\Pi_r^C = p_r^C - \left(\theta_{Cr}^E p_{Cr}^E 1^{-\sigma_{EC}} + (1 - \theta_{Cr}^E) \left[\prod_{i \notin FF} P_{ir}^{A_{ir}} \right]^{1-\sigma_{EC}} \right)^{\frac{1}{1-\sigma_{EC}}} = 0$$

7. Household energy demand:

$$\Pi_{Cr}^E = p_{Cr}^E - \left[\sum_{i \in FF} \theta_{iCr}^E p_{ir}^{A_{ir}} 1^{-\sigma_{FF,C}} \right]^{\frac{1}{1-\sigma_{FF,C}}} = 0$$

A.2. Market clearance conditions

8. Labour: $\bar{L}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial w_r}$

9. Capital: $\bar{K}_r = \sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial v_r}$

10. Natural resources: $\bar{Q}_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial q_{ir}} \quad i \in FF$

11. Output for domestic markets: $Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} = \sum_j A_{jr} \frac{\partial \Pi_{jr}^A}{\partial p_{ir}}$

12. Output for export markets: $Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^X} = \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}^X}$

13. Sector specific energy aggregate: $E_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$

14. Import aggregate: $M_{ir} = A_{ir} \frac{\partial \Pi_{ir}^A}{\partial p_{ir}^M}$

15. Armington aggregate: $A_{ir} = \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial p_{ir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{ir}^A}$

16. Household consumption:

$$C_r p_r^C = w_r \bar{L}_r + v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} + t_r^{CO_2} \bar{CO}_{2,r} + \bar{B}_r \\ + TR - p_{CGD,r} \bar{Y}_{CGD,r} - p_{G,r} \bar{Y}_{G,r}$$

17. Aggregate household energy consumption: $E_{Cr} = C_r \frac{\partial \Pi_r^C}{\partial p_{Cr}^E}$

18. Carbon emissions: $\bar{CO}_{2,r} = \sum_i A_{ir} a_i^{CO_2}$

TABLE A1
Sets

i	Sectors and goods
j	Aliased with i
r	Regions
s	Aliased with r
EG	All energy goods: Coal, crude oil, refined oil, gas and electricity
FF	Primary fossil fuels: Coal, crude oil and gas
LQ	Liquid fuels: Crude oil and gas

TABLE A2
Activity variables

Y_{ir}	Production in sector i and region r
E_{ir}	Aggregate energy input in sector i and region r
M_{ir}	Aggregate imports of good i and region r
A_{dir}	Armington aggregate for demand category d of good i in region r
C_r	Aggregate household consumption in region r
E_{Cr}	Aggregate household energy consumption in region r

TABLE A3
Price variables

p_{ir}	Output price of good i produced in region r for domestic market
p_{ir}^X	Output price of good i produced in region r for export market
p_{ir}^E	Price of aggregate energy in sector i and region r
p_{ir}^M	Import price aggregate for good i imported to region r
p_{ir}^A	Price of Armington good i in region r
p_r^C	Price of aggregate household consumption in region r
p_{Cr}^E	Price of aggregate household energy consumption in region r
w_r	Wage rate in region r
v_r	Price of capital services in region r
q_{ir}	Rent to natural resources in region r ($i \in \text{FF}$)
$t_r^{CO_2}$	CO ₂ tax in region r

TABLE A4
Cost shares

θ_{ir}^X	Share of exports in sector i and region r
θ_{ijr}	Share of intermediate good j in sector i and region r ($i \notin \text{FF}$)
θ_{ir}^{KLE}	Share of KLE aggregate in sector i and region r ($i \notin \text{FF}$)
θ_{ir}^E	Share of energy in the KLE aggregate of sector i and region r ($i \notin \text{FF}$)

(continued)

TABLE A4 *concluded*

α_{ir}^T	Share of labour ($T=L$) or capital ($T=K$) in sector i and region r ($i \notin FF$)
θ_{ir}^Q	Share of natural resources in sector i of region r ($i \in FF$)
θ_{ir}^{FF}	Share of good i ($T=i$), labor ($T=L$), or capital ($T=K$) in sector i and region r ($i \in FF$)
θ_{ir}^{COA}	Share of coal in fossil fuel demand by sector i in region r ($i \notin FF$)
θ_{ir}^{ELE}	Share of electricity in energy demand by sector i in region r
β_{jir}	Share of liquid fossil fuel j in energy demand by sector i in region r ($i \in FF, j \in LQ$)
θ_{isr}^M	Share of imports of good i from region s to region r
θ_{ir}^A	Share of domestic variety in Armington good i of region r
θ_{Cr}^E	Share of fossil fuel composite in aggregate household consumption in region r
γ_{ir}	Share of non-energy good i in non-e. household consumption demand in region r
θ_{iCr}^E	Share of fossil fuel i in household energy consumption in region r

TABLE A5

Endowments and emissions coefficients

\bar{L}_r	Aggregate labour endowment for region r
\bar{K}_r	Aggregate capital endowment for region r
\bar{Q}_{ir}	Endowment of natural resource i for region r ($i \in FF$)
\bar{B}_r	Balance of payment deficit or surplus in region r (note: $\sum_r \bar{B}_r = 0$)
\bar{CO}_2	Endowment of carbon emission rights in region r
$a_i^{CO_2}$	Carbon emissions coefficient for fossil fuel i ($i \in FF$)

TABLE A6

Elasticities

η	Transformation between production for the domestic market and production for the export	4
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.5
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities $\mu_{CRU} = 0.5, \mu_{COL} = 0.5, \text{ and } \mu_{GAS} = 1.$	endog.
σ_{ELE}	Substitution between electricity and the fossil fuel aggregate in production	0.3
σ_{COA}	Substitution between coal and the liquid fossil fuel composite in production	0.5
σ_A	Substitution between the import aggregate and the domestic input	2
σ_M	Substitution between imports from different regions	4
σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

For the sensitivity analysis reported in section 4, the lower and upper values of the uniform probability distributions for six key elasticities are as follows:

$1 < \sigma_A < 4; 2 < \sigma_M < 8; 0.25 < \sigma_{KLE} < 0.75; 0.6 < \sigma_C < 1; 0.25 < \mu_{CRU} < 1; 0.25 < \mu_{COL} < 1.$

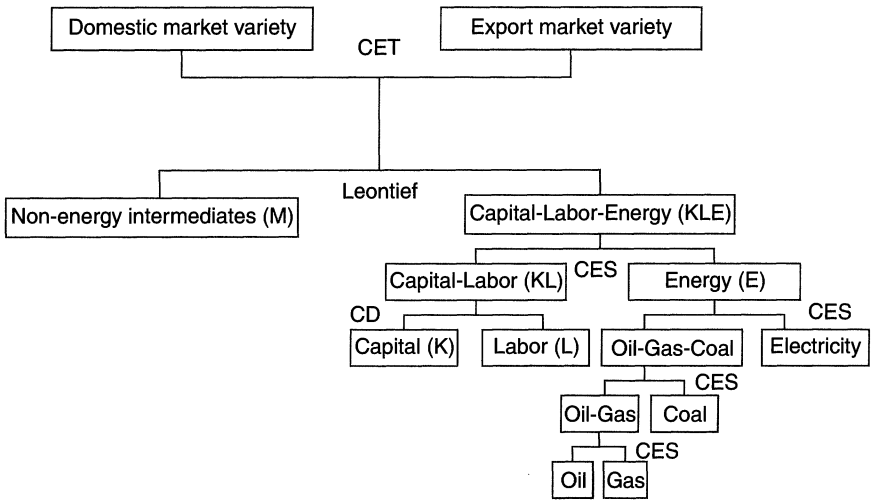


FIGURE A1 Nesting in non-fossil fuel production

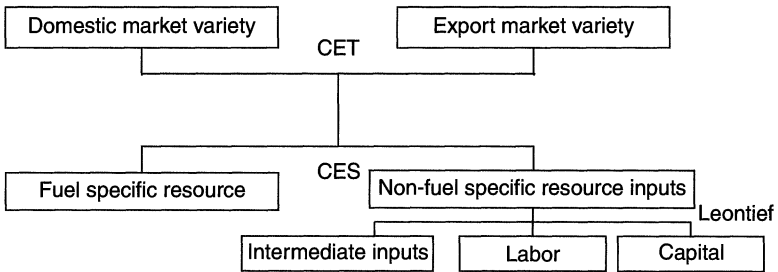


FIGURE A2 Nesting in fossil fuel production

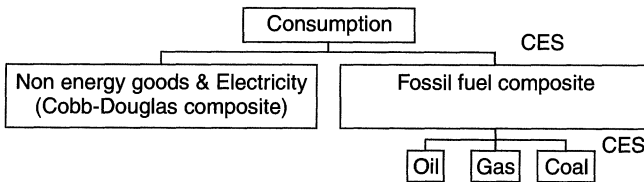


FIGURE A3 Nesting in household consumption

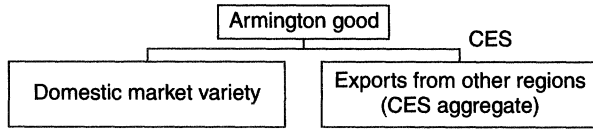


FIGURE A4 Nesting in Armington production