

Climate Politics From Kyoto to Bonn: From Little to Nothing ?!?

Christoph Böhringer*

Abstract

We investigate how the U.S. withdrawal and the provisions of the Bonn climate policy conference on sink credits and emissions trading will change the economic and environmental impacts of the Kyoto Protocol in its original form. Based on simulations with a large-scale computable general equilibrium model, we find that U.S. withdrawal and the amendments of Bonn boil down the Kyoto Protocol to business-as-usual without binding emission constraint. U.S. compliance under the new Bonn provisions, on the other hand, would accommodate a substantial cut in global emissions at relatively small compliance costs for OECD countries.

Key words: climate policy, emission trading, computable general equilibrium

JEL classification: D58, Q43, Q58

We would like to thank Sergey Paltsev, Thomas F. Rutherford, Till Requate, Peter Zapfel, Philippe Tulkens, Andreas Löschel and four anonymous referees for helpful comments. Financial support from the European Commission under the projects *Climate Change Policy and Global Trade* (CCGT) and *Greenhouse Gases Emission Control Strategies* (GECS) is gratefully acknowledged. Regarding any remaining inadequacies, the usual caveat applies.

* Head of Department, Environmental and Resource Economics, Centre for European Economic Research (ZEW), P.O. Box 103443, D-68034 Mannheim, Germany. E-mail: boehringer@zew.de

1. Introduction

The Kyoto Protocol negotiated in 1997 during the third Conference of Parties (COP3), requires industrialized countries to limit their emissions of greenhouse gases (GHG). In its original version, the Protocol was supposed to cut down the GHG emissions of the industrialized countries during the period 2008-2012 by an average of 5.2 % below their 1990 levels. The agreement will not enter into force, however, 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 CO₂ emissions (the most important GHG) in 1990.

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.¹

The U.S. withdrawal triggered a discussion among the remaining industrialized countries about whether or not to implement the Protocol in the absence of the U.S. The EU declared itself leader in a strategy of ratification without the U.S. Yet - in addition to EU approval - entering into force of the Protocol requires ratification by Japan, the Former Soviet Union (Russia and Ukraine), as well as Eastern Europe to get the necessary quorum. Russia, Ukraine and Eastern Europe were assumed to ratify, since they expect larger revenues from selling surplus emission rights.² Japan confirmed its interest to keep the treaty alive bearing the name of its imperial city. However, it also stressed that the Protocol would make sense only if the U.S. - as the world's biggest polluter - would carry out the treaty.

In this context, delegates from 180 countries met in Bonn during July 2001, most of them determined to rescue the Kyoto global warming treaty from collapsing after a decade of negotiations.³ The negotiating parties agreed on a compromise paper which demanded numerous concessions, especially by the EU. Australia, Canada, New Zealand, Japan, and Russia were allowed a substantial credit for carbon dioxide sinks, namely forests and agricultural soils that store the greenhouse gas. The latter is supposed to considerably water

¹ In 1997, the U.S. Senate unanimously passed the Byrd-Hagel resolution, which makes "meaningful" participation of developing countries a *conditio sine qua non* for ratification (The Byrd-Hagel Resolution, U.S. Senate, 12 June 1997, 105th Congress, 1st Session, Senate Resolution 98). Given that U.S. ratification requires a 2/3 majority in the Senate, the prospects for ratification have been rather small over the years, irrespective of the latest move under the Bush administration.

² Under the Kyoto Protocol, Eastern Europe, Ukraine and, particularly Russia received much higher emission entitlements than they are expected to emit under business-as-usual between 2008-2012 (see e.g. Paltsev 2000). They will sell their excessive emission rights if industrialized countries can trade emission rights among each other to minimize overall costs of abatement.

³ The Bonn conference was the official follow-up of COP6 in Den Haag preceding COP7 in Marrakesh.

down the provisions of the Protocol as originally agreed in 1997. Moreover, the restrictive position held by the EU with respect to the permissible scope of emissions trading between industrialized countries is no longer held. The latest version of the Kyoto Protocol does not foresee any concrete caps on the share of emissions reductions a country can meet through the purchase of permits from other industrialized countries, nor does it envision a cap on the amount of permits it can sell.⁴ In fact, this means that Russia, Ukraine and Eastern Europe will be able to sell all their surplus emission permits - usually referred to as *hot air* - which may significantly increase the effective emissions under the Kyoto Protocol as compared to strictly domestic action.⁵ COP7 in Marrakesh (November 2001) confirmed the outcome of Bonn with one smaller change in sink credit accounting: The sink potential from forest management for Russia was doubled.⁶ Otherwise, the Marrakesh conference was mainly concerned with technical and legal details in the implementation of emissions trading (e.g. monitoring and verification) as well as concrete sanction mechanisms in the case of non-compliance.

Meanwhile, there is an extensive literature providing quantitative evidence on the economic effects of the Kyoto Protocol (see e.g. Weyant 1999 for a summary report). However, this literature does not incorporate the most recent substantial changes in international climate politics, i.e. the U.S. withdrawal from the Kyoto Protocol and the provisions of the Bonn conference on sink credits and emissions trading.⁷

The objective of this paper is to assess how the U.S. withdrawal and the amendments of the Bonn conference will change the economic and environmental impacts of the Kyoto Protocol in its original form. Based on simulations with a large-scale computable general equilibrium model of global trade and energy use, our key findings can be summarized as follows:

⁴ It was agreed that the use of emissions trading "shall be supplemental to domestic action and domestic action shall thus constitute a significant element of the effort made by each Party to meet its quantified emission limitation and reduction commitments ..." (UNFCCC 2001). The undefined term "significant" gives sufficient leeway for comprehensive trading.

⁵ The effects of restrictions on permit imports and exports have been discussed more recently in Bernstein et al. (1999), Bollen et al. (1999), Criqui et al. (1999), Böhringer (2000), Ellerman and Wing (2000), or Rose and Stevens (2001).

⁶ Concretely, 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. Our simulations incorporate the outcome of COP7.

⁷ One exception is Hagem and Holtmark (2001), who investigate the implications of U.S. withdrawal using a simple partial equilibrium model of fossil fuel markets. Apart from the neglect of important general equilibrium effects, the main shortcoming of their study is the exclusive focus on emission impacts without a link to economic impacts.

- (i) Non-compliance of the U.S. reduces environmental effectiveness of the Kyoto Protocol practically to zero if there are no restrictions to hot air sales from Russia, Ukraine and Eastern Europe. In this case, the demand for emission permits of remaining OECD countries is sufficiently small to drive down the price of permits close to zero (if Kyoto targets had not been relaxed for sink credits) or to zero (if Kyoto targets are updated with sink credits) given the large supply of surplus emission rights from Russia, Ukraine and Eastern Europe. In short, the Kyoto Protocol more or less boils down to business-as-usual without binding emission constraint.
- (ii) Restrictions on emissions trading in order to avoid hot air and to assure some environmental effectiveness for the case of U.S. withdrawal makes global abatement for non-U.S. OECD countries rather costly. For strictly domestic abatement, the reduction in global emissions only amounts to a third of the quantity that would be achieved for U.S. compliance, whereas total costs for abating OECD countries would remain roughly the same. Adoption of the EU cap proposal on the amount of tradable emissions, would not help to alleviate these adverse effects of U.S. withdrawal.
- (iii) Monopolistic permit supply by Russia, Ukraine, and Eastern Europe will prevent environmental effectiveness from falling to zero in the case of U.S. withdrawal but global emission reduction will nevertheless amount to only 1 % as compared to business-as-usual.
- (iv) Under U.S. compliance, adoption of sink credits together with unrestricted emissions trading, accommodates very small compliance costs for OECD while global emissions would still fall by roughly 4 %. The consumption loss to U.S. seems small enough - around 0.25 % of the business-as-usual consumption level - to justify hopes that the U.S. might rejoin the Kyoto Protocol during the next years.

The remainder of the paper is organized as follows. Section 2 provides a brief non-technical summary of the underlying modeling framework. Section 3 entails a description of the policy scenarios. Section 4 presents the interpretation of simulation results. Section 5 concludes.

2. Analytical Framework and Baseline Calibration

For our analysis, we use a standard static 7-sector, 12-region computable general equilibrium (CGE) model of the world economy (see Böhringer 2000 or Rutherford and Paltsev 2000).

The choice of sectors captures key dimensions in the analysis of carbon abatement such as differences in carbon intensities and the scope for substitutability across energy goods and carbon-intensive non-energy goods. The regional aggregation covers the Annex B parties as well as major non-Annex B regions that are central to the greenhouse gas issue. Table 1 summarizes the sectors and regions incorporated in our model. For the sake of brevity, we abstain here from details on sectoral and regional aggregation as well as a comprehensive (algebraic) model description, which are available as a download from <ftp://ftp.zew.de/pub/zew-docs/div/kyoto2bonn.pdf>.

Table 1: Overview of sectors and regions

Sectors		Countries	
<i>Energy</i>		<i>Annex B</i>	
COL	Coal	USA	United States
CRU	Crude oil	EUR	OECD Europe (incl. EFTA)
GAS	Natural gas	JPN	Japan
OIL	Refined oil products	CAN	Canada
ELE	Electricity	AUN	Australia, New Zealand
<i>Non-Energy</i>		CEA	Central and Eastern Europe
EIS	Energy-intensive sectors	FSU	Former Soviet Union
ROI	Rest of industry	<i>Non-Annex B</i>	
		CHN	China
		IND	India
		ASI	Rest of Asia
		MPC	Mexico and OPEC
		ROW	Rest of world

As is customary in applied general equilibrium analysis, the model is based on economic transactions in a particular benchmark year. Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities (see download for a summary of 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. The simulation results for emission abatement scenarios reported in section 4 are measured with respect to the *BAU* situation in 2010.

3. Policy Scenarios

The set of scenarios reflects alternative options for implementing the Kyoto Protocol along three important dimensions of climate change policy, which are laid out in the following.

A. Reduction Requirements

The Kyoto Protocol fixes GHG emission limits for industrialized countries as listed in Annex B of the Protocol. In our simulations we consider two different schemes of emission reduction targets:

OLD Option *OLD* considers a reduction target of 5.2 % on average for industrialized countries which the Kyoto Protocol originally aspired to.

NEW Option *NEW* accounts for carbon dioxide sinks as agreed on in Bonn and confirmed in Marrakesh: Countries can offset some of the CO₂ stored in their forests and farmlands to meet their emission limits.

Table 2 lists the original reduction targets (*OLD*) and revised targets (*NEW*) for Annex B countries accounting for potential sink credits (see also Appendix C in download).

Table 2: Original Kyoto reduction targets (*OLD*) and Bonn updates with sink credits (*NEW*)

	<i>OLD</i> Commitment ^a	<i>NEW</i> Commitment ^b
	(% of 1990 base year GHG emissions)	(% of 1990 base year GHG emissions)
USA	93.0	96.8
EUR	92.2	94.8
JPN	94.0	99.2
CAN	94.0	107.9
AUN	106.8	110.2
CEA	92.9	96.1
FSU	100.0	107.6

^a UNFCCC (1997)

^b Estimates by the European Commission (Nemry 2001)

Credits are composed of sinks from forest management, sinks from agricultural activities and sinks in CDM. Due to the lack of appropriate data, we assume that there are no costs to earning credits such that the overall economic gains and the relaxation of emission constraints through sink credits must be seen as an upper bound.

B. Scope of Emissions Trading

The Bonn compromise does not set clear limits on the magnitude of international emissions trading that the industrialized countries could engage in to achieve their targets. The scope of permissible emissions trading has been a major point of disagreement between the U.S. and the EU. The EU wanted nations to make at least half of their emissions cuts within their own borders, whereas the U.S. wanted no limit on the purchase of emission rights from other countries.

In our simulations, we capture extreme points on the extent to which countries can meet their specific emission reduction commitment by abatement abroad (so-called where-flexibility). Unrestricted where-flexibility among Annex B countries should be considered the relevant policy option emerging from the Bonn compromise:

NTR Annex B countries are restricted to domestic action for meeting their emission reduction commitment.

TRD There is unrestricted emission trading between Annex B countries, which assures equalization of marginal abatement costs but also allows countries to sell off abundant emission rights (hot air) that they would not have required in the *NTR* case.

C. Participation of the U.S.

In March 2001, the new U.S. administration under President G. W. Bush declared with respect to the Kyoto Protocol that "we have no interest in implementing this treaty." Since then, the EU has tried hard to persuade the U.S. to rejoin the Kyoto Process - so far, however, without success. Even the Bonn compromise could not appease the U.S., although it resolves several of the demands the U.S. had raised in the past - particularly concerning sink credits and international permit trading. It is nonetheless important for the international climate policy process to investigate how the economic and environmental impacts of the Kyoto Protocol change depending on the involvement of the U.S. We therefore take into account two options which deliver a useful angle of comparison:

USin Option *USin* assumes that the U.S. will keep with its Kyoto commitment.

USout Option *USout* reflects the current situation of U.S. climate policy in assuming that the USA will not be part of the Kyoto Protocol.

Table 3 summarizes the set of core scenarios that result from the combination of policy options as laid out above.

Table 3: Overview of scenarios

	Emission Reduction		Emissions Trading		U.S. Participation	
	<i>OLD</i>	<i>NEW</i>	<i>NTR</i>	<i>TRD</i>	<i>USin</i>	<i>USout</i>
<i>USin_NTR_OLD</i>	X		X		X	
<i>USout_NTR_OLD</i>	X		X			X
<i>USin_TRD_OLD</i>	X			X	X	
<i>USout_TRD_OLD</i>	X			X		X
<i>USin_NTR_NEW</i>		X	X		X	
<i>USout_NTR_NEW</i>		X	X			X
<i>USin_TRD_NEW</i>		X		X	X	
<i>USout_TRD_NEW</i>		X		X		X

4. Simulation Results

The economic and environmental impacts induced by alternative scenarios for the implementation of the Kyoto Protocol are measured with respect to a *BAU* reference point in 2010 without emission abatement policies. When we report results for the aggregate of Annex B (Label: ANNEXB) or non-Annex B (Label: NONAB) in the Tables below, we assume that the U.S. only forms part of Annex B or OECD if it sticks to its Kyoto commitment (*USin* scenarios), otherwise the aggregate of non-Annex B takes the U.S. into account. It should be noted that scenarios *USin_NTR_OLD* and *USin_TRD_OLD* reflect the policy settings that have been studied extensively in the literature on the economic impacts of the Kyoto Protocol. These simulations are repeated here to provide a consistent basis of comparison with the new scenarios capturing the implications of U.S. withdrawal and sink credits. All the results for *USin_NTR_OLD* and *USin_TRD_OLD* are in line with the quantitative estimates reported in previous studies (see e.g. Weyant 1999).

A. Compliance of the U.S. - No Emissions Trading

We start discussion of simulation results for the scenarios *USin_NTR_OLD* and *USin_NTR_NEW* where the U.S. meets its Kyoto targets (in the *OLD* or *NEW* version), and

reduction commitments are met exclusively by domestic action of Annex B countries. The potential economic impacts reported in Table 4 indicate why the U.S. has withdrawn from the Protocol and why JPN, CAN as well as AUN have pushed hard for the relaxation of their Kyoto targets via the accounting of sinks and unlimited Annex B emissions trading.

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). The marginal abatement costs per ton of carbon under *USin_NTR_OLD* are as follows: USA 170 USD, EUR 168 USD, JPN 394 USD, CAN 193 USD, and AUN 85 USD.⁸ Abatement in OECD countries produces significant spillovers to non-abating regions through induced changes in international prices, i.e. the terms of trade.⁹

Most important are changes on international fuel markets for crude oil, gas and coal. The cutback in global demand for fossil fuels implies a significant drop of their prices providing economic gains to fossil fuel importers and losses to fossil fuel exporters. These fossil fuel market effects explain most of the impacts for non-abating countries. The economic implications of international price changes on non-energy markets are more complex. Higher energy costs raise the prices of non-energy goods (particularly energy-intensive goods) produced in abating countries. Countries that import these goods suffer from higher prices to the extent that they can not substitute away towards cheaper imports of non-abating countries. The ease of substitution not only determines the implicit burden shifting via non-energy exports from abating countries but also the extent to which non-abating countries achieve a competitive advantage vis-à-vis abating exporters. The gain in market shares due to substitution effects may be partially offset by an opposite scale effect: Due to reduced economic activity and income, import demand by the group of abating countries (here: Annex

⁸ From a single country perspective, there is a straightforward monotonous correlation between the level of cutback, the induced marginal abatement cost and the associated infra-marginal consumption loss. However, these relationships do not necessarily carry over for the comparison across countries, since differences in energy prices, energy intensities, substitution elasticities, etc. across countries also matter.

⁹ See Babiker, Reilly and Jacoby (2000) or Böhringer and Rutherford (2002) for an elaborate discussion of terms-of-trade effects from GHG abatement policies.

B) declines, and this exerts a downward pressure on the export prices of non-abating countries.

Less stringent emission targets as adopted in Bonn reduce consumption losses of the Annex B group by more than 25 % - the adjustment costs to OECD countries, however, remain substantial.¹⁰

With respect to environmental effectiveness, domestic abatement by Annex B countries implies a global reduction of carbon emission by 9 % (*OLD*) or 7.9 % (*NEW*) compared to *BAU*. Leakage, which is mainly caused by increased fossil fuel demand of non-abating countries and shifts in the pattern of energy-intensive trade, amounts to more than 10 %.¹¹

B. Withdrawal of the U.S. - No Emissions Trading

Next, we move to the economic and environmental implications of U.S. withdrawal for the *NTR* cases, which are reported under columns *USout_NTR* for the *OLD* and *NEW* targets in Table 4. The induced changes in consumption illustrate the importance of terms-of-trade effects. In comparison to U.S. compliance, EUR and JPN are worse off because international fuel prices under U.S. withdrawal are not depressed as much and, therefore, terms-of-trade gains for fuel importers decrease. The latter effect becomes even more obvious for non-abating developing countries IDI and ASI. Fuel exporters such as CAN, FSU, MPC or ROW, on the other hand, do better. The key message of Table 4, however, is that U.S. withdrawal dramatically reduces cost-effectiveness of global emission reduction. Total costs for remaining Annex B countries slightly increase while global emission reduction drops by a factor of 3 as compared to the scenario where the U.S. does not drop out.¹²

In other words: If the consumption losses for non-U.S. Annex B countries under *USin_NTR* correspond to their average willingness-to-pay, as would be the case ideally, U.S. withdrawal from the Kyoto Protocol would require a tripling of this willingness-to-pay.

¹⁰ The decrease in consumption losses comes along with the reduction in marginal abatement costs. The latter are as follows under *USin_NTR_NEW* : USA 143 USD, EUR 139 USD, JPN 297 USD, CAN 108 USD, and AUN 69 USD.

¹¹ Leakage is measured as the ratio of emission change in non-abating region(s) over aggregate emission reduction in abating regions. A leakage rate of 10 % implies that non-abating countries offset a tenth of the carbon reduction achieved in abating countries.

¹² Non-participation of the U.S. not only implies that the direct U.S. contribution to global emission reduction drops out. It also implies that counterproductive leakage more than doubles with the U.S. becoming the major source of leakage.

Table 4: U.S. compliance versus U.S. withdrawal for the *NTR* case (*OLD* and *NEW* targets)

	Emission Reduction Target: <i>OLD</i>					
	Consumption (in % vs. <i>BAU</i>)		CO ₂ -Cut (in % vs. <i>BAU</i>)		Leakage (in %)	
	<i>USin_NTR</i>	<i>USout_NTR</i>	<i>USin_NTR</i>	<i>USout_NTR</i>	<i>USin_NTR</i>	<i>USout_NTR</i>
USA	-0.67	0.02	28.2	-2	9.1	
EUR	-0.44	-0.53	18.2	18.2		
JPN	-0.88	-0.95	28.3	28.3		
CAN	-1.81	-1.09	28.9	28.9		
AUN	-1.05	-0.90	16.8	16.8		
CEA	0.68	0.35	-4.9	-3.7		
FSU	-0.66	-0.50	-4.8	-3.5		
CHN	-0.09	-0.09	-1.4	-0.9	2.5	3.7
IND	0.24	0.09	-1.5	-0.8	0.6	0.7
MPC	-0.73	-0.29	-3.7	-1.9	3	3.5
ASI	0.14	0	-3.8	-2.3	2	2.8
ROW	-0.07	-0.08	-4.3	-2.7	3.1	4.5
TOTAL	-0.36	-0.25	9	3.1	11.1	24.2
NONAB	-0.08	-0.02				
ANNEXB	-0.46	-0.48				
OECD	-0.47	-0.50				
	Emission Reduction Target: <i>NEW</i>					
	Consumption (in % vs. <i>BAU</i>)		CO ₂ -Cut (in % vs. <i>BAU</i>)		Leakage (in %)	
	<i>USin_NTR</i>	<i>USout_NTR</i>	<i>USin_NTR</i>	<i>USout_NTR</i>	<i>USin_NTR</i>	<i>USout_NTR</i>
USA	-0.52	0.02	25.2	-1.6	8.8	
EUR	-0.34	-0.42	15.9	15.9		
JPN	-0.63	-0.70	24.4	24.4		
CAN	-1.03	-0.46	18.3	18.3		
AUN	-0.88	-0.74	14.2	14.2		
CEA	0.57	0.28	-4.3	-3.2		
FSU	-0.60	-0.45	-4.1	-3		
CHN	-0.07	-0.07	-1.2	-0.8	2.4	3.6
IND	0.21	0.07	-1.3	-0.7	0.6	0.7
MPC	-0.62	-0.23	-3.2	-1.5	2.9	3.4
ASI	0.12	0	-3.2	-1.8	1.9	2.6
ROW	-0.06	-0.06	-3.7	-2.3	3	4.5
TOTAL	-0.28	-0.19	7.9	2.7	10.9	23.6
NONAB	-0.07	-0.02				
ANNEXB	-0.34	-0.36				
OECD	-0.34	-0.37				

Given empirical evidence on the low willingness-to-pay for climate change even in industrialized countries, the dilemma from a political economy point of view becomes obvious. Besides, the *USout_NTR*-scenarios would also appear rather unfair to voters in abating non-U.S. OECD countries, since they have to bear substantial adjustment costs while the U.S. economy remains basically unaffected.

But not only acceptance in remaining OECD countries seems unrealistic. Independent of U.S. withdrawal, FSU wouldn't like any scenario without emissions trading because then it would face overall consumption losses due to negative terms-of-trade effects (in particular with respect to its gas and oil export revenues). In this context, it should be noted that the U.S. position has an important impact on the potential bargaining power of the FSU.

If the U.S. forms part of the abatement coalition, the issue of FSU-compliance won't matter at all for the *NTR* cases - neither in economic terms nor in environmental terms (FSU doesn't abate anyway!). However, U.S. withdrawal gives FSU a key leverage to achieve concessions from the remaining Annex B countries: Without the U.S., the enactment of the Kyoto Protocol requires acceptance by FSU, because otherwise ratifying countries would not contribute at least 55 % of the industrialized world's CO₂ emissions in 1990. Obviously, one key demand on behalf of FSU will be Annex B emissions trading without constraints from third parties on its permissible level of carbon exports.

C. Withdrawal of the U.S. - Emissions Trading

This leads us to the final set of core scenarios in which we consider the consequences of permit trading. As an outcome of the Bonn conference, there are no (clear) limits on the extent to which one Annex B country can meet its reduction commitment by purchasing emission rights from other Annex B countries. Tables 5 and 6 show the implications of unconstrained Annex B emissions trading, which - after Bonn - appears as a very realistic option.

Full Annex B trading reduces the aggregate Annex B costs of implementing Kyoto dramatically due to the equalization of marginal abatement costs across regions. All OECD countries benefit substantially from purchasing cheap emission abatement in CEA and FSU. However, consumption losses for USA, CAN and AUN are still non-negligible in those scenarios in which the U.S. sticks to its Kyoto commitment. Monetary transfers to CEA and FSU are large and provide major economic gains, in particular to FSU.

Table 5: Impacts of U.S. withdrawal for the *TRD* case and *OLD* targets

	Consumption (in % vs. <i>BAU</i>)			Marginal Abatement Costs (USD/ton C)		
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>
USA	-0.67	-0.40	0	170	61	
EUR	-0.44	-0.16	-0.03	168	61	7
JPN	-0.88	-0.15	-0.03	394	61	7
CAN	-1.81	-0.92	-0.10	193	61	7
AUN	-1.05	-0.82	-0.11	85	61	7
CEA	0.68	1.40	0.09	0	61	7
FSU	-0.66	7.67	0.81	0	61	7
CHN	-0.09	0.03	0			
IND	0.24	0.16	0.01			
MPC	-0.73	-0.45	-0.04			
ASI	0.14	0.15	0.01			
ROW	-0.07	-0.01	0			
TOTAL	-0.36	-0.06	0			
NONAB	-0.08	-0.03	0			
ANNEXB	-0.46	-0.07	0			
OECD	-0.47	-0.19	-0.02			
	CO ₂ -Cut (in % vs. <i>BAU</i>)			Leakage (in %)		
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>
USA	28.2	13.3	-0.2			0.8
EUR	18.2	7.5	1.1			
JPN	28.3	7.4	1.2			
CAN	28.9	12.4	2.2			
AUN	16.8	13.4	2.1			
CEA	-4.9	17.9	2.8			
FSU	-4.8	16.7	2.6			
CHN	-1.4	-1.3	-0.2	2.5	2.2	0.6
IND	-1.5	-1.1	-0.1	0.6	0.4	0.1
MPC	-3.7	-2.8	-0.3	3	2.3	0.5
ASI	-3.8	-2.5	-0.3	2	1.4	0.3
ROW	-4.3	-2.7	-0.3	3.1	1.9	0.5
TOTAL	9	5.8	0.5	11.1	8.2	2.8

Table 6: Impacts of U.S. withdrawal for the *TRD* case and *NEW* targets

	Consumption (in % vs. <i>BAU</i>)			Marginal Abatement Costs (USD/ton C)		
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>
USA	-0.52	-0.24	0	143	37	
EUR	-0.34	-0.08	0	139	37	0
JPN	-0.63	-0.08	0	297	37	0
CAN	-1.03	-0.45	0	108	37	0
AUN	-0.88	-0.53	0	69	37	0
CEA	0.57	0.87	0	0	37	0
FSU	-0.60	5.23	0	0	37	0
CHN	-0.07	0.02	0			
IND	0.21	0.10	0			
MPC	-0.62	-0.29	0			
ASI	0.12	0.09	0			
ROW	-0.06	-0.01	0			
TOTAL	-0.28	-0.03	0			
NONAB	-0.07	-0.02	0			
ANNEXB	-0.34	-0.03	0			
OECD	-0.34	-0.11	0			
	CO ₂ -Cut (in % vs. <i>BAU</i>)			Leakage (in %)		
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_TRD</i>
USA	25.2	8.6	0			0
EUR	15.9	4.8	0			
JPN	24.4	4.8	0			
CAN	18.3	8	0			
AUN	14.2	8.8	0			
CEA	-4.3	12	0			
FSU	-4.1	11.1	0			
CHN	-1.2	-0.8	0	2.4	1.7	0
IND	-1.3	-0.7	0	0.6	0.3	0
MPC	-3.2	-1.8	0	2.9	1.6	0
ASI	-3.2	-1.6	0	1.9	1	0
ROW	-3.7	-1.7	0	3	1.5	0
TOTAL	7.9	3.8	0	10.9	6	0

As expected, adoption of the less stringent emission reduction targets (*NEW*) not only reduces the burden to OECD countries but also the benefits to CEA and FSU from permit trading: The decline in abatement demand of OECD countries drives down the price of

tradable permits. Trade in emission rights reduces global leakage. However, global emission reduction under U.S. compliance drops by one third for the original Kyoto targets (*OLD*) and by one half for the revised Kyoto targets (*NEW*) as a consequence of hot air. This negative impact on global emission reduction should not obscure the fact that global emissions fall noticeably and average costs per emission reduction for abating OECD countries are much more favorable as compared to the cases without emission trading (*USin_NTR* and, in particular, *USout_NTR*).

U.S. withdrawal, joint with emissions trading between remaining Annex B countries, implies negligible costs for meeting the *OLD* Kyoto targets and zero costs for meeting the *NEW* Kyoto targets. Since the U.S., as the world largest potential buyer of emission rights, withdraws from the permit market, the price of emission permits falls close to zero in the *OLD* case. With relaxed Kyoto targets (*NEW*), the permit price even hits zero, as the demand of remaining Annex B countries is small relative to the supply of surplus emission rights from FSU and CEA. While U.S. withdrawal and unconstrained Annex B emissions trading sounds like good news from the aggregate cost side, the environmental effectiveness is more or less zero. In other words, Kyoto comes at no costs because the world economy and its emissions develop as under business-as-usual.

5. Sensitivity Analysis

The preceding section provided a comprehensive assessment of U.S. withdrawal, sink credits, and emissions trading under central case assumptions. We have performed a sensitivity analysis with respect to changes in several key assumptions: market structure of emissions trading, scope of emissions trading, and ease of substitution among traded goods. In this section, we summarize the implications of changes in underlying key assumptions. For the sake of compactness, all the numerical results are based on the revised Kyoto targets. While the magnitude of quantitative results can be altered as a consequence of model assumptions, we have found that all of our key insights remain robust. As for the previous Tables, it should be kept in mind that that the U.S. only forms part of Annex B or OECD if it sticks to its Kyoto commitment (*USin* scenarios), otherwise the aggregate of non-Annex B takes the U.S. into account (*USout* scenarios).

A. Monopolistic Permit Supply

Competitive behavior of FSU and CEA on the permit market may seem somewhat implausible for the case in which the international permit price falls to zero, and emission

sales therefore do not create any revenue. What will happen if these countries behave as monopolists restricting their supply in order to drive up the international carbon price? As a shortcut, we mimic such a behavior by imposing caps on emission right exports from FSU and CEA where rents from export quotas accrue to FSU and CEA respectively. Concretely, we assume that export quotas for FSU and CEA will be 0 %, 20 %, 40%, 60 %, 80 %, and 100 % of the difference between their business-as-usual emissions and their emission entitlements after the Bonn updates.¹³ Table 7 summarizes results for non-compliance of the U.S., and otherwise unrestricted intra-OECD emissions trading. As export quotas between 80 % and 100 % imply an excess supply of permits on international markets, i.e. no change vis-à-vis *BAU*, we have omitted the respective columns.

We have also listed the results for the scenario *USout_NTR_NEW* to accommodate the direct comparison with the *NTR* case. Column "0" of Table 7 captures a situation in which FSU and CEA will not export any emission rights but only intra-OECD emissions trading will take place. The latter cuts down compliance costs for the OECD by 13.5 % without loss of environmental effectiveness as compared to the no-emission-trading case (*USout_NTR_NEW*).

Table 7: Export quotas on hot air from FSU and CEA

	<i>USout_NTR_NEW</i>	0	20	40	60
Consumption (in % vs. <i>BAU</i>)					
CEA	0.28	0.28	0.45	0.42	0.25
FSU	-0.45	-0.40	2.10	2.60	1.70
TOTAL	-0.19	-0.16	-0.10	-0.05	-0.02
NONAB	-0.02	-0.01	-0.01	-0.01	0
ANNEXB	-0.36	-0.31	-0.18	-0.10	-0.04
OECD	-0.37	-0.32	-0.24	-0.16	-0.08
CO ₂ -Cut (in % vs. <i>BAU</i>)					
TOTAL	2.7	2.7	2	1.3	0.6
Leakage ^a (in %)					
TOTAL	24	24	17	11	5

^a Ratio of emission change in non-abating region over aggregate emission reduction in abating regions

¹³ Note that the case "100%", where FSU and CEA sell off total hot air, coincides with the scenario *USout_TRD_NEW*.

When FSU and CEA sell hot air, the international price of carbon permits as well as total OECD compliance costs fall towards larger amounts of hot air exports. The numerical results indicate that FSU would aim at restricting permits sales at 40 % of hot air in order to maximize consumption.¹⁴ In this case, global emission reduction as compared to *BAU* drops to roughly 1 %. Obviously, leakage rates decline with the increase in hot air sales as the latter relaxes the overall carbon emission constraint for abating Annex B countries.

Table 7 illustrates the potential trade-offs between environmental effectiveness and total costs of OECD compliance on the one hand, as well as burden sharing between OECD and FSU/CEA on the other hand.

B. EU Cap Proposal

In order to mitigate hot air, the EU called for restrictive ceilings on the amount of tradable emissions. According to the cap proposal by the EU Council of Environment (Baron et al. 1999), purchases or sales of emissions by Annex B countries may not exceed 5 percent of the weighted average of base year emissions and the assigned Kyoto emission budget. Table 8 reports the implications for economic costs and environmental effectiveness (columns: "*USin_EU*", "*USout_EU*").

Table 8: Implications of EU cap proposal

	<i>USin_NTR</i>	<i>USin_EU</i>	<i>USin_TRD</i>	<i>USout_NTR</i>	<i>USout_EU</i>	<i>USout_TRD</i>
Consumption (in % vs. <i>BAU</i>)						
USA	-0.52	-0.51	-0.24	0.02	0.01	0
TOTAL	-0.28	-0.22	-0.03	-0.19	-0.12	0
NONAB	-0.07	-0.06	-0.02	-0.02	-0.01	0
ANNEXB	-0.34	-0.28	-0.03	-0.36	-0.24	0
OECD	-0.34	-0.32	-0.11	-0.37	-0.28	0
CO ₂ -Cut (in % vs. <i>BAU</i>)						
TOTAL	7.9	7.3	3.8	2.7	2.2	0
Leakage (in %)						
TOTAL	10.9	9.9	6	23.6	19.3	0

¹⁴ Note that CEA prefers a slightly more restrictive export quota regime because the foregone revenues from permit sales would be more than offset from terms-of-trade gains on fossil fuel markets due to the larger fall in international fuel prices.

In comparison with unrestricted emissions trading, the EU cap proposal reduces hot air to a large extent. However, the restrictive ceilings also imply a substantial loss in overall efficiency since marginal abatement costs will differ substantially between various regions (causing also higher leakage rates as compared to the *TRD* case). In particular, the EU cap proposal provides very small efficiency gains to the U.S. vis-à-vis the *NTR* case which explains the stiff U.S. resistance to this plan during the climate negotiations. In almost the same manner as under *NTR*, U.S. withdrawal makes global abatement much more expensive for non-U.S. OECD countries under cost-effectiveness considerations.

C. Trade Elasticities

We represent trade in goods with an Armington structure. Imports are imperfect substitutes for domestically produced goods. The elasticity of substitution between imports and domestically produced goods, referred to as the Armington elasticity, measures how easily imports can substitute for domestic goods. In the sensitivity analysis, we vary the values of Armington elasticities to quantify the induced changes in trade impacts of carbon abatement policies.

In our central case, the elasticity of substitution between the domestic good and the import aggregate is set equal to 4.0, and the elasticity of imports from different regions within the import aggregate is set equal to 8.0. In the sensitivity analysis, we either halve (*low case*) or double (*high case*) these values.

While the change in elasticities has only a negligible impact on total adjustment costs¹⁵, the ease of substitution affects the distribution of costs via changes in regions' primary abatement costs and secondary terms-of-trade effects. In the absence of terms-of-trade effects, the cost of carbon abatement moves inversely with trade elasticities because countries can more easily substitute away from carbon-intensive inputs into production and consumption. On the other hand, the trade elasticity determines the extent to which domestic abatement costs can be passed further to trading partners. With lower elasticities, a country importing carbon-intensive goods from a trading partner with high marginal abatement costs is less able to substitute away from the more expensive imports to the cheaper domestically produced goods. Our sensitivity analysis indicates that abating countries (ANNEXB) are worse off for higher trade elasticities indicating their reduced scope for effective tax burden shifting. On the

¹⁵ In general, total welfare costs of emissions constraints on the global economy decline towards higher trade elasticities.

other hand, non-abating countries (NONAB) face less adverse spillover impacts towards higher elasticities because (i) they can more readily substitute away from expensive energy-intensive goods of abating countries, and (ii) they can take greater advantage of their lower domestic production costs in competing against the abating countries. With respect to environmental spillovers, higher trade elasticities enforce the adverse impacts on energy-intensive industries in abating regions which leads to an increase in the global leakage rate.

Table 9: Implications of alternative Armington elasticities

Armington elasticities: <i>low</i>				
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_NTR</i>	<i>USout_TRD</i>
Consumption (in % vs. <i>BAU</i>)				
TOTAL	-0.28	-0.04	-0.19	0
NONAB	-0.13	-0.05	-0.03	0
ANNEXB	-0.33	-0.03	-0.35	0
OECD	-0.33	-0.12	-0.36	0
CO ₂ -Cut (in % vs. <i>BAU</i>)				
TOTAL	8.3	4.2	3	0
Leakage (in %)				
TOTAL	8.4	4.5	19.7	0
Armington elasticities: <i>high</i>				
	<i>USin_NTR</i>	<i>USin_TRD</i>	<i>USout_NTR</i>	<i>USout_TRD</i>
Consumption (in % vs. <i>BAU</i>)				
TOTAL	-0.28	-0.02	-0.19	0
NONAB	-0.05	-0.01	-0.01	0
ANNEXB	-0.35	-0.03	-0.37	0
OECD	-0.35	-0.10	-0.39	0
CO ₂ -Cut (in % vs. <i>BAU</i>)				
TOTAL	7.4	3.4	2.4	0
Leakage (in %)				
TOTAL	15.3	7.8	29.7	0

6. Conclusions

In this paper, we investigated different scenarios for implementing the Kyoto Protocol, combining alternative options along three important policy dimensions: U.S. compliance versus U.S. withdrawal, domestic action versus unrestricted Annex B emissions trading, and the original Kyoto targets versus the relaxed targets of Bonn.

Our results clearly indicate that U.S. withdrawal from the Protocol implies a dramatic reduction in environmental effectiveness. If emission trading among remaining Annex B countries becomes more or less unrestricted, which seems to be rather likely after the Bonn outcome, the reduction of global carbon emissions as compared to *BAU* will fall to zero. The reason is that supply of surplus emission rights from Russia, Ukraine, and Eastern Europe is large relative to the demand from OECD countries other than the U.S., driving down the permit price close to zero (if Kyoto targets had not been relaxed for sink credits) or to zero (if Kyoto targets are updated with sink credits).

If remaining OECD countries would opt for strictly domestic action in order to prevent hot air, global carbon emissions could be reduced by 2.7 % (with sink credits) or 3.1 % (without sink credits). However, the global emission cutback would then only amount to roughly a third of the value that could be achieved for U.S. compliance while remaining OECD countries would suffer more or less the same non-negligible adjustment costs. Implicit willingness-to-pay, thus, would have to triple in these countries. Such a policy appears rather unacceptable to citizens in non-U.S. OECD countries - not only with regard to overall cost-effectiveness but also with respect to fairness considerations. The same reasoning applies to the case there non-U.S. OECD countries would adopt the EU cap proposal instead of strictly domestic action.

If Russia, Ukraine, and Eastern Europe restrict the supply of hot air to drive up the price of permits, this would prevent environmental effectiveness from falling to zero in the case of U.S. withdrawal. Global emission reduction under monopolistic permit supply will nevertheless amount to only 1 % as compared to business-as-usual.

Policy makers have welcomed the outcome of the Bonn climate negotiations as a decisive breakthrough in international climate politics. The environmental effects can not be the reason for celebration: Sink credits, hot air through emissions trading and, in particular, the continued U.S. withdrawal will make Kyoto ineffective in environmental terms.

However, it can be argued that - even without any effective emission cutback - the ratification of Kyoto is crucial for the further policy process of climate protection. Failure might have thrown back the efforts to climate protection by several years. Hopes remain that the U.S. might rejoin the Protocol under the new conditions. Compliance costs to the U.S. economy seem rather moderate, which could enhance the domestic U.S. political pressure in favor of coordinated international abatement. Starting from a ratified Kyoto Protocol, it may be also easier to achieve effective GHG emission reduction in the second commitment period of the Kyoto Protocol after 2012.

There are some caveats to our analysis which may be addressed in future research once the relevant information and data is available: First, we do not cover a further commitment period after 2012 which might influence behavior in the first commitment (e.g. through banking of emission permits). Second, we assume for the case of U.S. withdrawal that the U.S. will not undertake any domestic policies to cut GHG emissions. Third, no other greenhouse gases besides CO₂ are incorporated in our analysis, i.e., we apply GHG emission reduction targets to carbon dioxide only, which is the most important GHG among industrialized countries.

References

- Baron, R., M. Bosi, A. Lanza and J. Pershing (1999), A Preliminary Analysis of the EU Proposals on the Kyoto Mechanisms, Energy and Environment Division, International Energy Agency, <http://www.iea.org/new/releases/1999/eurpro/eurlong.html>
- Bernstein, P., D. Montgomery, T. F. Rutherford and G. Yang (1999), Effects of Restrictions on International Permit Trading: The MS-MRT Model, *The Energy Journal – Special Issue*, 221-257.
- Böhringer, C. (2000), Cooling Down Hot Air - A Global CGE Analysis of Post-Kyoto Carbon Abatement Strategies, *Energy Policy* 28, 779-789.
- Böhringer, C. and T. F. Rutherford (2002), Carbon Abatement and International Spillovers, *Environmental and Resource Economics* (forthcoming).
- Bollen, J., A. Gielen and H. Timmer (1999), Clubs, Ceilings and CDM – Macroeconomics of Compliance with the Kyoto Protocol, *The Energy Journal – Special Issue*, 177-206.
- Criqui, P., S. Mima and L. Viguier (1999), Marginal abatement costs of CO₂ emission reductions, geographical flexibility and concrete ceilings: an assessment using the POLES model, *Energy Policy* 27, 585-602.
- DOE (1998), Department of Energy, Annual Energy Outlook (AEO 1998), Energy Information Administration, <http://www.eia.doe.gov>
- Ellerman, A.D. and I. S. Wing (2000), Complementarity: An Invitation for Monopsony, *The Energy Journal* 21 (4), 29-59.
- Hagem, C. and B. Holtmark, From small to insignificant: Climate impact of the Kyoto Protocol with and without US, CICERO Policy Note 2001:1, <http://www.cicero.uio.no>
- Nemry, F. (2001), LULUCF39 v4 - Quantitative implications of the decision -/CP.7 on LULUCF, Personal Communication.

- Paltsev, S.V. (2000), The Kyoto Protocol: Hot Air for Russia?, University of Colorado, Working Paper 00-9, http://debreu.colorado.edu/projects/sergey_hotair.pdf
- Paltsev, S.V. (2001), The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage, *The Energy Journal* 22 (4), 53-79.
- Rose, A., and B. Stevens (2001), An Economic Analysis of Flexible Permit Trading in the Kyoto Protocol, *International Environmental Agreements* 1, 219-42.
- Rutherford, T.F. and S.V. Paltsev (2000), GTAP-Energy in GAMS, University of Colorado, Working Paper 00-2, <http://debreu.colorado.edu/download/gtap-eg.pdf>
- UNFCCC (1997), United Nations Framework Convention on Climate Change, *Kyoto Protocol to the United Nations Framework Convention on Climate Change*, FCCC/CP/L.7/Add.1, Kyoto.
- Weyant, J. (ed) (1999), The Costs of the Kyoto Protocol: A Multi-Model Evaluation, *The Energy Journal*, Special Issue.

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 interchangeably 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 with $Y = \varphi(k, x)$ the production functions. 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:

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

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:

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

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:

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

and the demand for factor f in sector i is:

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

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

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

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

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

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 $\nu = \text{COL, CRU, GAS}$) and those for non-fossil fuels (in our case $n = \text{EIS, ELE, OIL, ROI}$).

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.):

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

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} :

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

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:

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

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 :

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

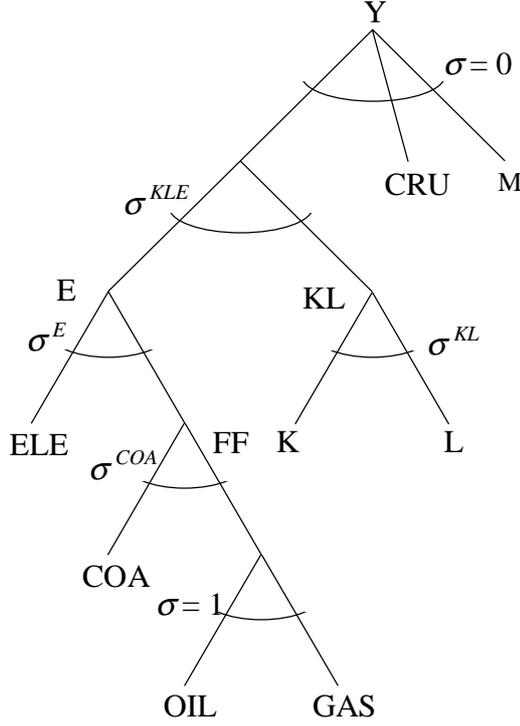


Figure A.1: Nesting structure of non-fossil fuel production

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:

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

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

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

with γ_{vr} the resource value share.

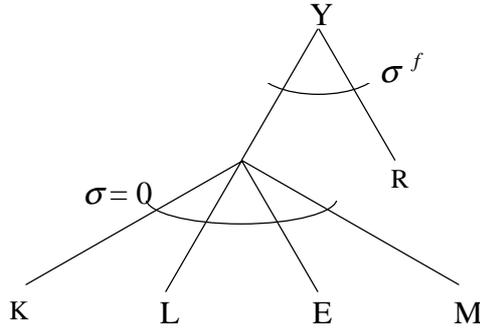


Figure A.2: Nesting structure for fossil fuel production

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:

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

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:

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

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

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

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:

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

and

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

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

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

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:

$$\text{Max}_{d_{ir}} W_r(d_{ir}) \quad \text{s.t.} \quad \text{INC}_r = \sum_f w_{fr} \bar{k}_{fr} + \text{TR}_r = \sum_i p_{ir} d_{ir} \quad [19]$$

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:

$$pw_r = e_r(p_{ir}) \quad [20]$$

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

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

with $\overline{\text{INC}}$ 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 ($fe = \text{COL, OIL, GAS}$) trading off at a constant elasticity of substitution. The CES utility function is:

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

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 CO₂ 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:

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

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

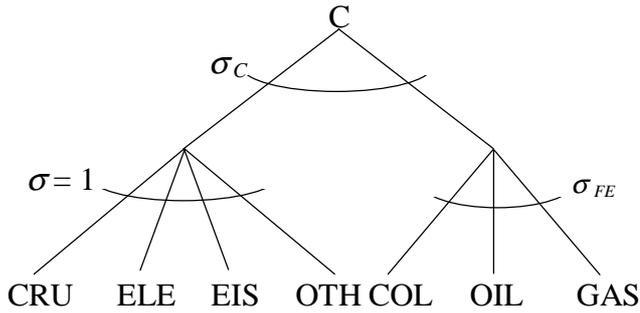


Figure A.3: Structure of household demand

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:

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

with $\sigma^{ir} = 1/(1 + \eta)$ 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:

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

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:

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

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 CO2 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:

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

with a_i the carbon emissions coefficient for fossil fuel i and τ the shadow price of CO₂ in region r associated with the carbon emission restriction:

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

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:

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

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:

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

with PA the price of the Armington composite. π_{ir}^Z is the per unit zero profit function with Z the name assigned to the associated production activity. The derivation of π_{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:

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

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

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

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

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

where PM is the import price.

Primary factor endowment equals primary factor demand:

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

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

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

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 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	0.8
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	4.0
σ^M Substitution elasticity between imports from different regions forming the import composite	8.0
σ^{tr} Transformation elasticity domestic vs. export	2.0
Exogenous supply elasticities of fossil fuels ε	
Crude oil	1.0
Coal	1.0
Natural gas	1.0

Appendix B: Regional and Sectoral Aggregation

The model is calibrated to the energy-economy data set GTAP-EG which combines economic data from the Global Trade Analysis Project (GTAP) database with energy flows and energy prices from OECD International Energy Agency (IEA) statistics (Rutherford and Paltsev 2000). The GTAP-EG data set encompasses 22 goods/sectors (5 of which are energy goods/sectors) and 45 regions. 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			
<i>Energy</i>			
COL	Coal	COL	
CRU	Crude oil	CRU	
GAS	Natural gas	GAS	
OIL	Refined oil products	OIL	
ELE	Electricity	ELE	
<i>Non-Energy</i>			
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

<i>Annex B</i>		
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
<i>Non-Annex B</i>		
CHN	China	CHN, HKG
IND	India	IND
ASI	Other Asia	KOR, LKA, MYS, PHL, RAS, SGP, THA, TWN, VNM
MPC	Mexico and OPEC	IDN, MEX, RME, RNF, VEN
ROW	Rest of world	MAR, ROW, RSA, RSS, SAF, TUR

Appendix C: GHG Emission Reduction Targets for Annex B countries

	Label ^a	Original Kyoto Targets (<i>OLD</i>) ^b (% of 1990 base year GHG emissions)	Revised Targets (<i>NEW</i>) ^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)