Appendix:

Economic and Environmental Impacts

of the Kyoto Protocol

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Appendix A: 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 as compared to 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, labor, energy and material (KLEM).
- A representative agent (RA) in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labor 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 labor, capital and fossil-fuel resources are exogenous. Labor 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_{ir}^{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 A.1 – A.6 explain the notations for variables and parameters employed within our algebraic exposition. Figures A.1 – A.4 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:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A}$$

$$-\theta_{ir}^{KLE}\left[\theta_{ir}^{E} p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E})\left(w_r^{\alpha_{jr}^{L}} v_r^{\alpha_{jr}^{K}}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad i \notin FF$$

2. Production of fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}}$$

$$-\left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q})\left(\theta_{Lir}^{FF} w_r + \theta_{Kir}^{FF} v_r + \sum_j \theta_{jir}^{FF} p_{jr}^{A}\right)^{1-\sigma_{Q,i}}\right]^{\frac{1}{1-\sigma_{Q,i}}} = 0 \qquad i \in FF$$

3. Sector-specific energy aggregate:

$$\prod_{ir}^{E} = p_{ir}^{E} - \left\{ \theta_{ir}^{ELE} p_{\{ELE,r\}}^{A^{1-\sigma_{ELE}}} + (1-\theta_{ir}^{ELE}) \right.$$

$$\left. \left[\theta_{ir}^{COA} p_{\{COA,r\}}^{A^{1-\sigma_{COA}}} + (1-\theta_{ir}^{COA})\left(\prod_{j \in LQ} p_{jr}^{A^{\beta_{jir}}}\right)^{1-\sigma_{COA}}\right]^{\frac{1-\sigma_{ELE}}{1-\sigma_{COA}}} \right\}^{\frac{1}{1-\sigma_{ELE}}} = 0$$

4. Armington aggregate: $$\prod_{ir}^{A} = p_{ir}^{A} - \left[\left(\theta_{ir}^{A} p_{ir}^{1-\sigma_A} + (1-\theta_{ir}^{A}) p_{ir}^{M^{1-\sigma_A}}\right)^{\frac{1}{1-\sigma_A}} + t_r^{CO2} a_i^{CO2}\right] = 0$$

5. Aggregate imports across import regions: $$\prod_{ir}^{M} = p_{ir}^{M} - \left(\sum_s \theta_{isr}^{M} p_{is}^{X\ 1-\sigma_M}\right)^{\frac{1}{1-\sigma_M}} = 0$$

6. Household consumption demand:

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

7. Household energy demand: $\prod_{Cr}^{E} = p_{Cr}^{E} - \left[\sum_{i \in FF} \theta_{iCr}^{E} \; p_{ir}^{A\; 1-\sigma_{FF,C}} \right]^{\frac{1}{1-\sigma_{FF,C}}} = 0$

A.2 Market Clearance Conditions

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

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

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

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:

$$C_r p_r^C = w_r \overline{L}_r + v_r \overline{K}_r + \sum_{j \in FF} q_{jr} \overline{Q}_{jr} + t_r^{CO2} \overline{CO2}_r + \overline{B}_r + TR - p_{CGD,r} \overline{Y}_{CGD,r} - p_{G,r} \overline{Y}_{G,r}$$

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

18. Carbon emissions: $\overline{CO2}_r = \sum_i A_{ir} a_i^{CO2}$

Table A.1: 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 A.2: 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 A.3: 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 $\in$ FF)
t_r^{CO2}	CO_2 tax in region *r*

Table A.4: Cost shares

θ_{ir}^{X}	Share of exports in sector *i* and region *r*
θ_{jir}	Share of intermediate good *j* in sector *i* and region *r* (i$\notin$FF)
θ_{ir}^{KLE}	Share of KLE aggregate in sector *i* and region *r* (i$\notin$FF)
θ_{ir}^{E}	Share of energy in the KLE aggregate of sector *i* and region *r* (i$\notin$FF)
α_{ir}^{T}	Share of labor (*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_{Tir}^{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$\notin$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 A.5: Endowments and emissions coefficients

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

Table A.6: 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 $\mu_{CRU} = 0.5$, $\mu_{COL} = 0.5$, 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:

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

Appendix B: Graphical Exposition of Functional Forms

Figure B.1: Nesting in non-fossil fuel production

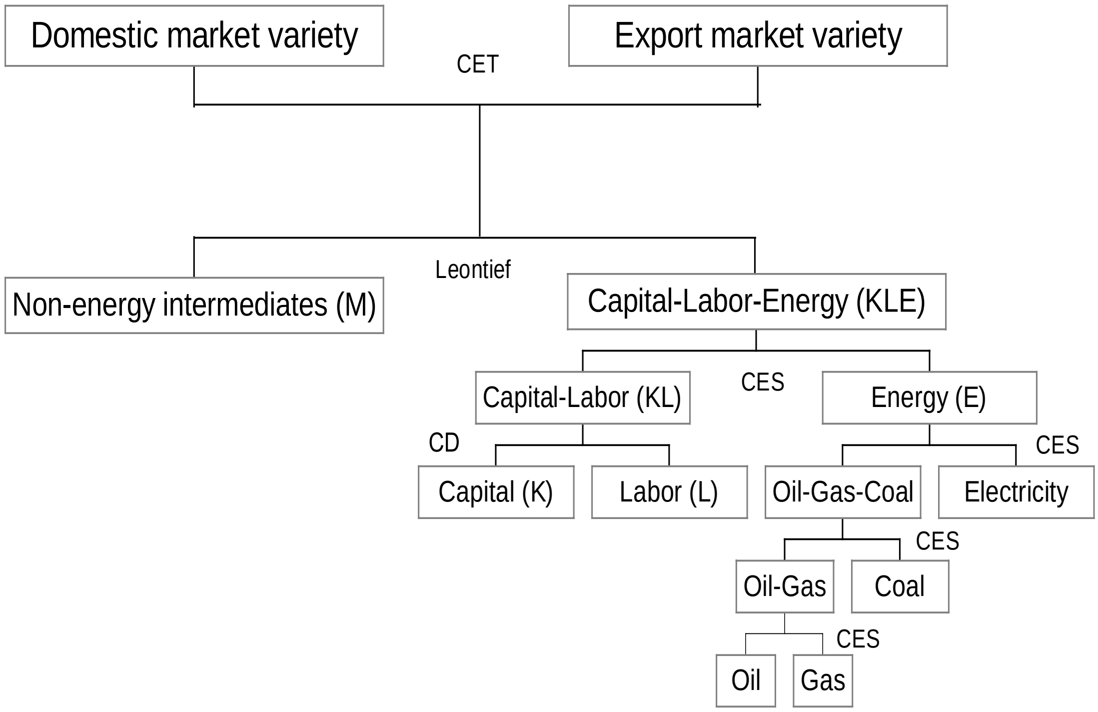


Figure B.2: Nesting in fossil fuel production

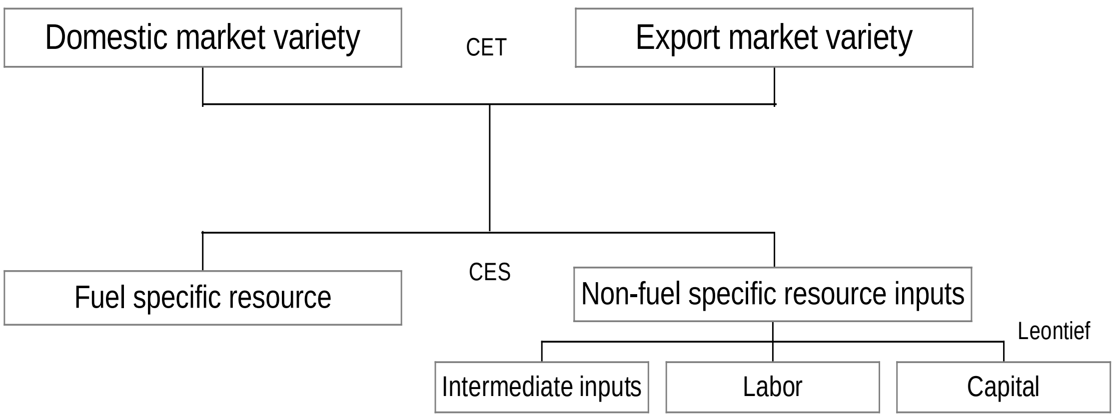


Figure B.3: Nesting in household consumption

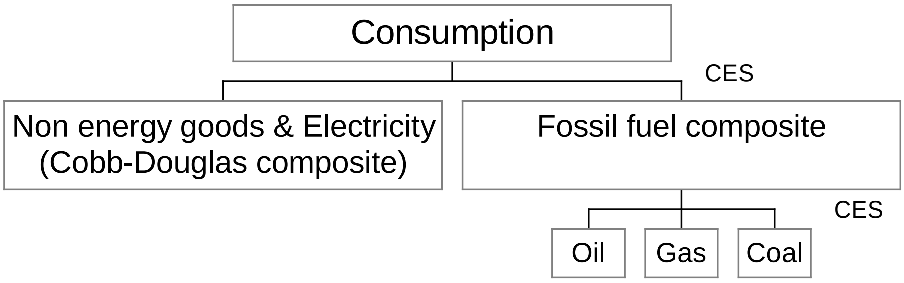
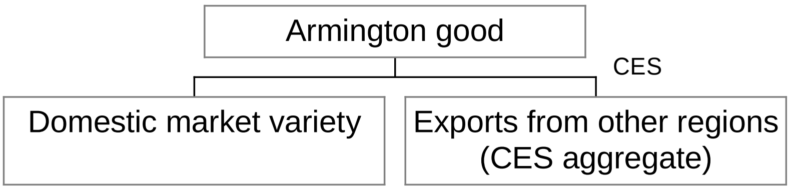


Figure B.4: Nesting in Armington production



Appendix C: Baseline Projections - Forward Calibration

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

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

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

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

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

Appendix D: Benchmark Data - Regional and Sectoral Aggregation

The model is built on a comprehensive energy-economy dataset that accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flow. The underlying data base is GTAP-EG which reconciles the most recent GTAP economic production and trade dataset for the year 1995 with OECD/IEA energy statistics for 50 regions and 23 sectors (Rutherford and Paltsev 2000). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Sectors and regions of the original GTAP-EG data set are aggregated according to Tables B.1 and B.2 to yield the model's sectors and regions.

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

* Set *i* in Table A.1 includes two additional artificial production sectors (CGD and G) that denote the (exogenous) demand for an investment/savings good (CGD) and the public good (G).

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

Appendix E: GHG Emission Reduction Targets for Annex B countries

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

[a] Label of aggregate model region which includes the respective Annex B country
[b] UNFCCC (1997)
[c] Estimates by the European Commission accounting for sink credits (Nemry 2001)