Post-Kyoto Climate Policy

A Computable General Equilibrium Analysis

based on Expert Judgements

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Downloadable Appendix

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

Appendix A: Expert Poll

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Post-Kyoto Commitments: An Expert Poll based on a Cross-Impact Matrix (CIM)

Objective

During COP6.5 and COP7 in Bonn and Marrakech, the implementation rules of the Kyoto Protocol for the 1st commitment period were finalized. The Protocol is now ready for ratification. However, there are large uncertainties with respect to the follow-up of climate protection policies in a 2nd commitment period. **Our poll is designed to identify key policy scenarios for a 2nd commitment period based on expert opinions. As contributing expert you will receive the summary of results before public release and you will be explicitly mentioned. Your answers will be treated anonymously.**

We perform the poll by means of a so-called cross-impact matrix (CIM), which allows for a systematic evaluation of expert opinions. Our cross-impact matrix captures cross-relationships between four key dimensions of a Post-Kyoto commitment: the required emission reduction for the abatement coalition within a 2nd commitment period, U.S. participation, inclusion of developing countries, and the allocation rule for emission entitlements.

You are asked to assess the interrelationship of these dimensions and the initial occurrence probabilities of events characterizing these dimensions within the CIM (attached to the end of this document).

Before you begin, we will briefly lay out the overall policy benchmark (see section 1), the scenario dimensions and specific events (see section 2), and the rules about how to fill out the cross-impact matrix (see section 3). For optional use, we have prepared an additional spreadsheet in the Appendix will provide you with the effective emission reduction requirements for central regions that are forming an abatement coalition under alternative allocation rules and global reduction targets.

Please read carefully before you start the CIM. If you have comments or questions on the design of our poll, please address *loeschel@zew.de*

1. Policy Benchmark

The Kyoto Protocol is likely to be ratified during 2002. We assume that the Kyoto Protocol will enter into force for its 1st commitment period between 2008 – 2012. The U.S. will keep with its withdrawal for the 1st commitment period. Furthermore, we assume that U.S. withdrawal, carbon sink credits, unrestricted permit trading, and larger hot air supplies from Russia and Ukraine will substantially relax the stringency of the Kyoto targets for signatory industrialized countries. Environmental effectiveness and compliance costs will be rather small even if Russia and Ukraine do act as monopoly suppliers of permits (restricting their supply of hot air). The recent Climate Change Plan for the US announced by President Bush on February 14, 2002 codifies more or less business-as-usual (BaU) emissions for the US.

In this context, the US and other industrialized countries (as listed in Annex B of the Kyoto Protocol) as well as the developing countries will negotiate on the design of a 2nd Post-Kyoto commitment period till 2020. For the sake of simplicity and data availability, we refer to the 2nd commitment period as lasting from 2010-2020, where the starting point 2010 represents simply BaU due to the reasons mentioned above. Without a 2nd commitment, i.e. under business-as-usual, global emissions will rise between 2010 and 2020 by 25%. We assume that members of the abatement coalition for the 2nd commitment period can freely trade in emission rights among each other.

In our abatement scenarios, we have deliberately omitted tax- or price-based regimes to cope with uncertainties, since we adopt a deterministic view on the future development of economic development and associated emissions.

2. Overview of Dimensions and Events

The CIM incorporates four key dimensions - A through D - of a Post-Kyoto commitment that are characterized by alternative events (see also Table 1 for a complete listing):

A **Required global emission reduction (relative to 2020 BaU level)** suggests four global emission reduction targets with respect to the business-as-usual emission level in 2020. Reduction *zero* (event a_1) reflects a situation without any emission abatement, i.e. 0% reduction. The remaining three reduction requirements are in line with alternative long-term IPCC stabilization targets of atmospheric CO_2 concentrations in 2100: *low* (event a_2)

represents a 10% emission reduction (650 ppmv in 2100), *middle* (event a_3) represents a 20% emission reduction (550 ppmv in 2100), and *high* (event a_4) represents a 30% emission reduction (450 ppmv in 2100). The global emission reduction must be achieved by 2020 by the abatement coalition. For example: If the abatement coalition consists only of industrialized countries, the latter must carry the whole global abatement burden while developing countries can proceed as under business-as-usual.

B **US participation in the abatement coalition** will be the case (event b_1: *yes*) or not. If the US is not member of the abatement coalition, it is either allowed to sell project-based emission reductions (event b_2: *no/trade*) or not (event b_3: *no*).

C **Participation of developing countries in the abatement coalition** will be the case (event c_1: *yes*) or not. If developing countries are not members of the abatement coalition, they are either allowed to sell project-based emission reductions (event c_2: *no/trade*) or not (event c_3: *no*).

D **Equity principle** considers four alternative burden-sharing rules of how the overall emission budget is translated into emission entitlements or emission reduction obligations:

- *egalitarian* (event d_1): Emission entitlements will be shared in equal-per-capita proportions based on population figures for 2010.
- *ability-to-pay* (event d_2): The absolute reduction requirement between 2010 and 2020 will be shared by regions according to their shares in GDP for the year 2010. The higher a region's share in GDP is, the higher its reduction requirement will be. Example: If a region has 70% of the abatement coalition’s total GDP in 2010, it is assigned 70% of the absolute reduction requirement that the coalition has to undertake.
- *polluter pays* (event d_3): The absolute reduction requirement between 2010 and 2020 will be shared by regions according to their shares in emissions for the year 2010. The higher a region's share in 2010 emissions is, the higher its reduction obligation will be.
- *sovereignty* (event d_4): Emission entitlements will be shared in proportion to the emissions in 2010.

Table 1: Dimensions and events of Post-Kyoto-Scenarios for 2010-2020

A.	*Required emission reduction (relative to 2020 level)*
	a_1: zero (0%)
	a_2: low (10%)
	a_3: middle (20%)
	a_4: high (30%)
B.	*US participation in the abatement coalition*
	b_1: yes
	b_2: no/trade
	b_3: no
C.	*Participation of developing countries in the abatement coalition*
	c_1: yes
	c_2: no/trade
	c_3: no
D.	*Equity principle*
	d_1: egalitarian (emission *entitlement* in proportion to population)
	d_2: ability-to-pay (emission *reduction* in proportion to GDP)
	d_3: polluter pays (emission *reduction* in proportion to emissions)
	d_4: sovereignty (emission *entitlement* in proportion to emissions)

3. Rules for Filling out the CIM

The events in the rows are the impact source for the events in the columns of the matrix (impact sinks). At each matrix intersection, the following question is asked: If the event in the row were to occur, how would it affect the probability of occurrence of the event in the column. Only quantify the **direct** impact! All indirect impacts will be accounted for automatically by means of the CIM method. Judgements are entered in the matrix cells. The probability of occurrence can be indicated with 7 different scales ranging from (-3) “reduces probability of occurrence significantly” to (+3) “increases probability of occurrence significantly”. For example: If you think that the adoption of the egalitarian equity principle (occurrence of event d_1) “reduces significantly” the probability of US participation (occurrence of event b_1), then insert “-3” in the matrix cell given by the intersection of row d_1 and column b_1.

In the last column of the CIM you must enter the initial occurrence probability of each event. Initial occurrence probabilities across all events within one scenario dimension must sum up to one!

Judgement may only be entered in the boxes of the CIM. Please fill in also your personnel information. The poll will be evaluated anonymously.

Appendix: Reduction Scenarios and Effective Reduction Requirements

Based on the most recent *International Energy Outlook* (IEO 2001: reference case) issued by the US Department of Energy, we have performed calculations to give an idea of which effective emission reduction requirements emerge across regions for the different scenarios. Table 2 lists the reduction requirements under the different scenarios for two geopolitical regions: *North* (industrialized world without US) and *South* (developing countries). The *US* is listed separately. Negative entries indicate a permissible increase in emissions over BaU emission levels in 2020.

Table 2: Effective Reduction Requirement in % vs. 2020 BaU emissions

	egalitarian (d_1)	ability-to-pay (d_2)	polluter pays (d_3)	sovereignty (d_4)
	Required emission reduction relative to 2020 level: zero (a_1) - 0%			
US included (b_1) and DC included (c_1)				
North	49	0	0	-11
South	-68	0	0	12
US	79	0	0	-10
US included (b_1) and DC excluded (c_2 or c_3)				
North	-31	0	0	0
US	46	0	0	0
US excluded (b_2 or b_3) and DC included (c_1)				
North	58	0	0	-14
South	-39	0	0	9
US excluded (b_2 or b_3) and DC excluded (c_2 or c_3)				
North	0	0	0	0
	Required emission reduction relative to 2020 level: low (a_2) - 10%			
US included (b_1) and DC included (c_1)				
North	54	15	11	0
South	-51	5	9	21
US	81	14	11	1
US included (b_1) and DC excluded (c_2 or c_3)				
North	-6	19	19	19
US	57	19	19	19
US excluded (b_2 or b_3) and DC included (c_1)				
North	63	21	14	1
South	-21	7	11	21
US excluded (b_2 or b_3) and DC excluded (c_2 or c_3)				
North	32	32	32	32

Table 2: continued

	egalitarian (d_1)	ability-to-pay (d_2)	polluter pays (d_3)	sovereignty (d_4)
	Required emission reduction relative to 2020 level: middle (a_3) - 20%			
US included (b_1) and DC included (c_1)				
North	59	29	22	11
South	-34	10	18	29
US	83	29	22	12
US included (b_1) and DC excluded (c_2 or c_3)				
North	19	38	38	38
US	67	38	38	38
US excluded (b_2 or b_3) and DC included (c_1)				
North	68	42	29	15
South	-4	14	23	32
US excluded (b_2 or b_3) and DC excluded (c_2 or c_3)				
North	63	63	63	63
	Required emission reduction relative to 2020 level: high (a_4) -30%			
US included (b_1) and DC included (c_1)				
North	64	44	33	23
South	-17	15	26	38
US	85	43	33	23
US included (b_1) and DC excluded (c_2 or c_3)				
North	44	57	57	57
US	77	56	57	57
US excluded (b_2 or b_3) and DC included (c_1)				
North	74	63	43	29
South	14	21	34	44
US excluded (b_2 or b_3) and DC excluded (c_2 or c_3)				
North	95	95	95	95

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Cross-Impact Matrix for Post-Kyoto-Commitment (2010-2020)

Dimensions	Events	Cross-Impact-Assessment															Probability
			a_1	a_2	a_3	a_4	b_1	b_2	b_3	c_1	c_2	c_3	d_1	d_2	d_3	d_4	
A Required emission reduction wrt 2020	a_1 zero (0%)	A a_1	–	–	–	–											
	a_2 low (10%)	a_2	–	–	–	–											
	a_3 middle (20%)	a_3	–	–	–	–											
	a_4 high (30%)	a_4	–	–	–	–											
B US partici-pation	b_1 yes	B b_1					–	–	–								**
	b_2 no/trade	b_2					–	–	–								**
	b_3 no	b_3					–	–	–								**
C Developing countries	c_1 yes	C c_1								–	–	–					
	c_2 no/trade	c_2								–	–	–					
	c_3 no	c_3								–	–	–					
D Equity principle	d_1 egalitarian	D d_1					*						–	–	–	–	
	d_2 ability-to-pay	d_2											–	–	–	–	
	d_3 polluter pays	d_3											–	–	–	–	
	d_4 sovereignty	d_4											–	–	–	–	

Scale

-3	reduces probability of occurrence significantly	1	increases probability of occurrence slightly
-2	reduces probability of occurrence	2	increases probability of occurrence
-1	reduces probability of occurrence slightly	3	increases probability of occurrence significantly
0	no influence on the probability of occurrence		

Note: Probabilities in each box of the last column add to 1!

** Example* If you think that the occurrence of event d_1 reduces significantly the probability of occurrence of b_1, then insert "-3" in the matrix cell given by the intersection of row d_1 and column b_1

** **Example**

$P_{b_1} = 0.4$, $P_{b_2} = 0.2$, $P_{b_3} = 0.4$

Appendix B: Cross-Impact Model

Cross-impact analysis was initially suggested by T. Gordon and O. Helmer in Kaiser-Aluminium's FUTURE game (Gordon and Hayward, 1968; Helmer, 1972). The first step to implement a cross-impact model is the definition of the set of possible future events A_i with m descriptors ($D_1,..., D_m$), each of which can take on $n_j \in \mathbb{N}$ different states (j = 1,..., m). Overall, there are $n = \sum_{j=1}^{m} n_j$ different descriptor states (events) $A_1,..., A_n$ (or, if a double index is used in which the first index describes the descriptor and the second index the state, $A_{11},..., A_{mn_m}$). As to further notation: $\tilde{n}_i = \sum_{j=1}^{i} n_j$. If a descriptor D_i takes on the state A_{ij}, then A_{ij} = 1 and allother A_{iv} = 0 for $v \neq j$. Altogether, there is a set of S different scenarios with $|S| = \prod_{j=1}^{m} n_j$, which yields x_s scenario probabilities to be estimated ($s \in \{1,...,|S|\}$). The scenario probabilities assess the joint occurrence of the m states of the respective scenarios.

The basic concept of cross-impact analysis is that the occurrence of an event A_i will affect the likelihood that other events A_j will occur. The strength and mode (unrelated, inhibiting or enhancing) of the interaction between event A_i and event A_j are characterized by cross-impact numbers k_{ij} (in our case: $k_{ij} \in \{-3,...,3\}$), which form a cross-impact matrix $K_{n \times n} = (k_{ij})$. Among the individual matrix elements, $n^2 - \sum_{i=1}^{m} n_i^2$ potential interactions ("cross impacts") have to be assessed. The diagonal block sub-matrices are set to zero.

Let p_j denote the subjective estimate of the a priori (marginal) probability of occurrence of event A_j, where $p_j \in [0,1]$ $\forall j$ and $\sum_{j=\tilde{n}_{i-1}+1}^{\tilde{n}_i} p_j = 1$ $\forall i$. The future states of descriptors are defined such that at least one of them will occur in the future - however, one does not know in advance which. For the sake of convenience, we use a single index notation hereafter and assume that the indices refer to states of different descriptor. The joint probability of the set of events $(A_{i_1},...,A_{i_l})$, $l \in \{2,...,m\}$ and $i_j \in \{1,...,n\}$, is given by $p_{i_1,...,i_l}$. Since the estimation of higher-order probabilities turns out to be extremely difficult (Mitchell et al. 1977), we simulate the joint probabilities for interdependent events, most importantly the scenario probabilities. We modify the BASICS simulation technique as proposed by Honton et al. (1984) for scenario generation using only estimations of marginal probabilities together with cross impacts in order to determine the joint scenario probabilities x_s.

Within our poll, the expert assesses the future of climate protection in terms of potential interactions and probabilities of events. We have considered m = 4 events with n_1 =

4, n_2 = 3, n_3 = 3, and n_4 = 4 different states. Thus, there are n = 14 different descriptors and marginal probabilities to be estimated. $|S|$ amounts to 4·3·3·4 = 144 different scenarios while the experts must assess $14^2 - \left(4^2 + 3^2 + 3^2 + 4^2\right)$ = 146 cross impacts. Once the elements of the cross-impact model have all been specified, we use a Monte Carlo technique to obtain a representative random sample. (Note that the BASICS method differs from our approach in that no Monte Carlo simulations performed.)

In order to generate a single scenario from the total set of marginal probability p_i and cross-impact information k_{ij}, we apply the following four-step heuristic procedure (see also Mißler-Behr, 1993):

1. Select an event A_j at random and decide its occurrence or non-occurrence on the basis of the assigned a priori probabilities.

The first event A_j is selected at random taking into account the expert assessment of marginal probabilities. A random number generator is used to decide whether A_j occurs or not. Next, the marginal probability of the selected event A_j gets adjusted: p_j = 1 in the case of occurrence and p_j = 0 in the case of non-occurrence. In the case of event occurrence, all other marginal probabilities p_μ of the different states of the respective descriptor D_l, $\mu \in \left\{\tilde{n}_{l-1}+1,...,\tilde{n}_l\right\}$ and $\mu \neq j$, are set to zero.

2. Adjust the probability of the remaining events A_i according to the cross impacts assessed by the experts.

The cross impacts k_{ij} describe the impacts of occurrence of event A_j on A_i. In addition, we have to estimate $\bar{k}_{ij}$, i.e. the interactions between A_j on A_i in the case of non-occurrence of event A_j. Since in the case of non-occurrence of state A_j of descriptor D_l another state A_μ ($\mu \in \left\{\tilde{n}_{l-1}+1,...,\tilde{n}_l\right\}$ and $\mu \neq j$) of descriptor D_l must occur affecting A_i, the impact of non-occurrence of A_j is estimated as the average impact of the occurrence of all other states A_μ of descriptor D_l on A_i: $\bar{K}_{n\times n} = \left(\bar{k}_{ji}\right) = round\left[\sum_{\substack{\mu=\tilde{n}_{l-1}+1 \\ \mu\neq j}}^{\tilde{n}_l} k_{\mu i} \Big/ \left(n_l - 1\right)\right]$. In case of occurence of event A_j, the cross impacts k_{ji} are transformed into a cross-impact factor f_{ji} to generate a cross-impact factor matrix:

$$F_{n\times n} = \left(f_{ji}\right) \text{ with } f_{ji} = \begin{cases} k_{ji}+1 & \text{for } k_{ji} \ge 0 \\ \dfrac{1}{\left|k_{ji}\right|+1} & \text{for } k_{ji} < 0 \end{cases}$$

In the case of non-occurrence of A_j the matrix F is built using $\bar{k}_{ji}$ instead of k_{ji}. From the odds of occurrence of event A_i, $w_i \in [0, \infty]$, $w_i = p_i / (1 - p_i)$, the probability of occurrence can be derived as $p_i = w_i / (1 - w_i)$. The occurrence of event A_j changes the odds of A_i depending on the cross-impact factor f_{ji}: $w_{i(j)} = w_i \cdot f_{ji}$. The odds are reduced if A_j has an inhibiting impact on A_i, i.e. $f_{ji} \in (0,1)$. They remain unchanged if A_j has no impact on A_i, i.e. $f_{ji} = 1$, and the odds are increased if A_j has an enhancing impact on A_i, i.e. $f_{ji} > 1$. The adjusted probability $p_{i(j)}$ of A_i is given by $p_{i(j)} = w_{i(j)} / (1 - w_{i(j)}) = p_i \cdot f_{ji} / \left[1 - p_i\left(f_{ji} - 1\right)\right]$. As the adjusted probabilities of each descriptor do not necessarily add up to one, the $p_{i(j)}$'s for all events are normalized. The normalized adjusted probability of state A_i of descriptor D_l is given by: $p'_{i(j)} = p_{i(j)} \Big/ \sum_{\mu=\tilde{n}_{l-1}+1}^{\tilde{n}_l} p_{\mu(j)}$, $i \in \left\{\tilde{n}_{l-1}+1, \ldots, \tilde{n}_l\right\}$.

3. Select another event A_l among the remaining ones and decide its occurrence or non-occurrence on the basis of the adjusted probabilities.

To select another event the distance d_i, $i = 1,\ldots, n$; $d_i \in [0, 0{,}5]$ of all adjusted event probabilities $p'_{i(j)}$ to zero or one is calculated:

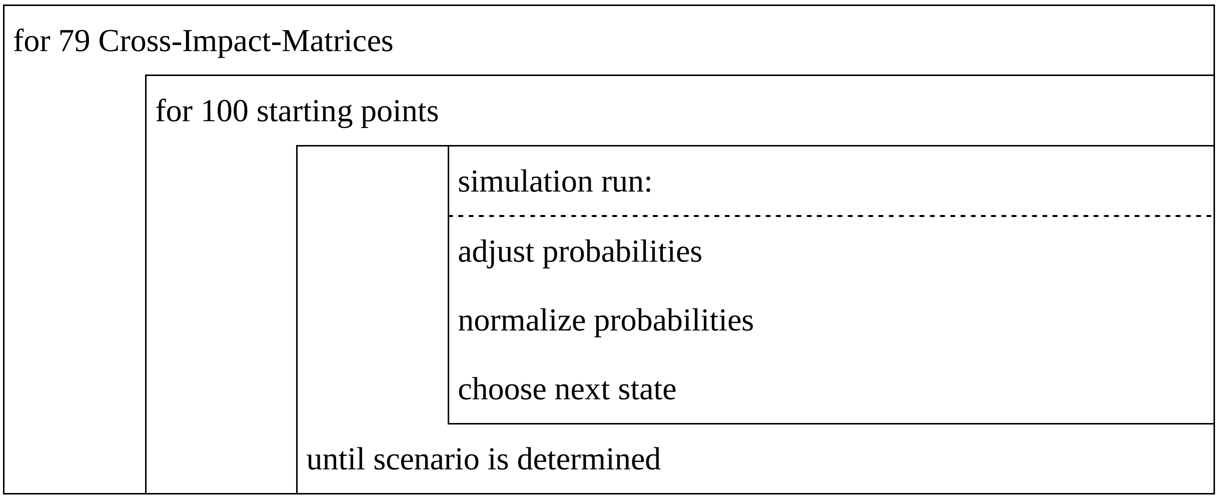
$$d_i = \begin{cases} p'_{i(j)} & \text{for } p'_{i(j)} < 0.5 \\ 1 - p'_{i(j)} & \text{for } p'_{i(j)} \ge 0.5 \end{cases}$$

The closer $p'_{i(j)}$ comes to zero, the more probable it is that A_i does not occur. The closer $p'_{i(j)}$ comes to one, the more probable it is that A_i occurs. Therefore, the next event A_l is chosen according to the following rule: $\left(\min_{i\in\{1,\ldots n\}} d_i = d_l\right) \wedge \left(d_l > 0\right)$. Whenever $0 < p'_{l(j)} < 0.5$, it is assumed that A_l occurs. If $0.5 \le p'_{l(j)} < 1$, it is assumed that A_l does not occur. In case $\left(\min_i d_i\right)$ is not unambiguous, a random number generator is used to select an event. The condition $(d_l > 0)$ assures that only events are selected for which adjusted probabilities are not already set to zero or one.

4. Continue Step 2 and Step 3 until all events in the set have been decided.
One simulation run is finished as soon as all events have either occurred or not occurred. The result of the simulation is one scenario.

In our application, the simulation procedure is repeated 100 times for each of the 79 experts' cross-impact matrices. This yields a set of marginal probabilities and scenario probabilities that adequately represents the interaction between a number of uncertain developments. Figure B.1 summarizes the simulation procedure in use to derive the scenario probabilities.

Figure B.1: Simulation procedure



Appendix C: CGE Model Summary

Non-technical model description

Figure C.1 provides a diagrammatic structure of the multi-region, multi-sector CGE model underlying our comparative-static analysis of Post-Kyoto policy scenarios. Primary factors of region *r* include labor $\overline{L}_r$, capital $\overline{K}_r$, and fossil-fuel resources $\overline{Q}_{ff,r}$. Labor and capital are intersectorally mobile within a region but cannot move between regions. A specific resource is used in the production of fossil fuels *ff* (crude oil, coal and gas), resulting in upward sloping supply schedules.

Production Y_{ir} of commodities *i* in region *r* other than primary fossil fuels is captured by aggregate production functions which characterize technology through substitution possibilities between various inputs. Nested constant elasticity of substitution (CES) cost functions with three levels are employed to specify the substitution possibilities in domestic production between capital, labor, energy and non-energy, intermediate inputs, i.e. material. At the top level, non-energy inputs are employed in fixed proportions with an aggregate of energy, capital and labor. At the second level, a CES function describes the substitution possibilities between the energy aggregate and the aggregate of labor and capital. Finally, at the third level, capital and labor trade off with a constant elasticity of substitution. As to the formation of the energy aggregate, we allow sufficient levels of nesting to permit substitution between primary energy types, as well as substitution between a primary energy composite and secondary energy, i.e. electricity.

Final demand C_r in each region is determined by a representative agent RA_r, who maximizes utility subject to a budget constraint with fixed investment. Total income of the representative household consists of factor income and tax revenues. Final demand of the representative agent is given as a CES composite which combines consumption of an energy aggregate with a non-energy consumption bundle. Substitution patterns within the non-energy consumption bundle are reflected via Cobb-Douglas functions. The energy aggregate in final demand consists of the various energy goods trading off at a constant elasticity of substitution.

All goods used on the domestic market in intermediate and final demand correspond to a CES composite A_{ir} of the domestically produced variety and a CES import aggregate M_{ir} of the same variety from the other regions (the so-called Armington good – see Armington, 1969). Domestic production either enters the formation of the Armington good or is exported to satisfy the import demand of other regions.

The tax system includes all types of indirect taxes (production taxes or subsidies *ty*, intermediate taxes *ti*, consumption taxes *tc*, as well as tariffs *tm* and *tx*) which are used to finance a fixed level of public good provision. A lump-sum tax on the representative household balances the public budget.

Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. The underlying data base is GTAP-EG for the year 1997 which provides a consistent representation of energy markets in physical units as well as detailed accounts of regional production and consumption as well as bilateral trade flow (see McDougall et al., 1998; Rutherford and Paltsev, 2000). The benchmark data, and the regional and sectoral aggregation are described in section *Benchmark Data - Regional and Sectoral Aggregation* of this Appendix.

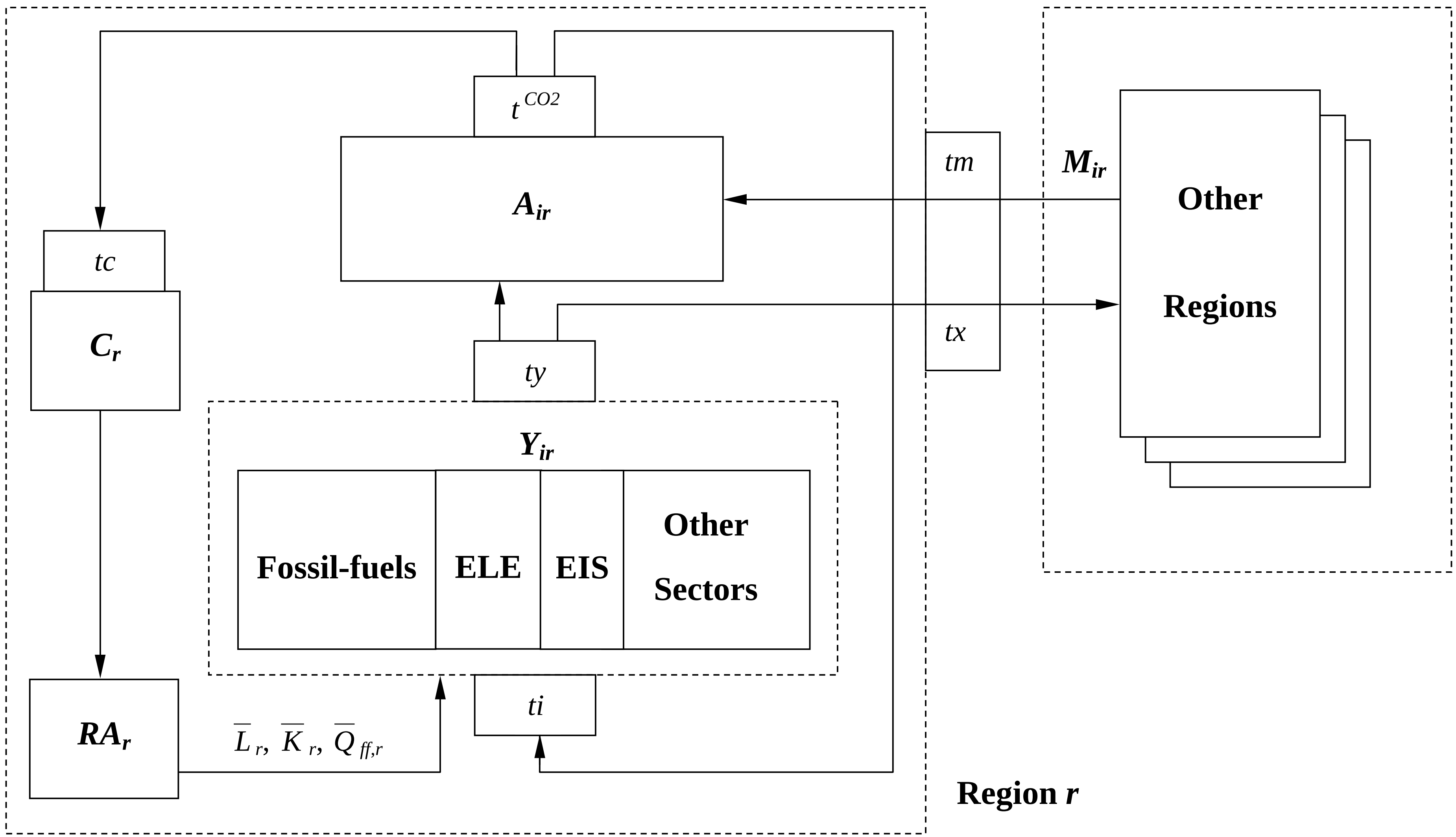
The economic effects of future climate policies depend on the extent to which emission reduction targets constrain the respective economies in their *BaU* development (without emission limits). Thus, the magnitude and distribution of adjustment costs to Post-Kyoto commitments depend on the *BaU* projections for GDP, fuel prices, energy efficiency improvements, etc. In our comparative-static framework, we infer the *BaU* structure of the model's regions for the target year (in our case: 2020) using recent projections for economic development from the International Energy Outlook (DOE, 2001) (see section *Baseline Projections - Forward Calibration* of this Appendix). We then measure the costs of abatement relative to that baseline.

Numerically, the model is formulated as a mixed complementarity problem (MCP) in GAMS (Brooke et al. 1996; Rutherford, 1999) and solved using PATH (Dirkse and Ferris, 1995).

Algebraic model description

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 (Hotelling's lemma), which appear subsequently in the market clearance conditions.

Figure C.1: Diagrammatic model structure



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 C.1 – C.6 explain the notations for variables and parameters employed within our algebraic exposition. Figures C.1 – C.4 provide a graphical exposition of the production and final consumption structure.

Zero Profit Conditions

1. Production of goods except fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \sum_{j \notin EG} \theta_{jir} p_{jr}^{A} - \theta_{ir}^{KLE}\left[\theta_{ir}^{E} p_{ir}^{E\ 1-\sigma_{KLE}} + (1-\theta_{ir}^{E})\left(w_{r}^{\alpha_{jr}^{L}} v_{r}^{\alpha_{jr}^{K}}\right)^{1-\sigma_{KLE}}\right]^{\frac{1}{1-\sigma_{KLE}}} = 0 \qquad i \notin \mathrm{FF}$$

2. Production of fossil fuels:

$$\prod_{ir}^{Y} = \left(\theta_{ir}^{X} p_{ir}^{X^{1-\eta}} + (1-\theta_{ir}^{X}) p_{ir}^{1-\eta}\right)^{\frac{1}{1-\eta}} - \left[\theta_{ir}^{Q} q_{ir}^{1-\sigma_{Q,i}} + (1-\theta_{ir}^{Q})\left(\theta_{Lir}^{FF} w_{r} + \theta_{Kir}^{FF} v_{r} + \sum_{j} \theta_{jir}^{FF} p_{jr}^{A}\right)^{1-\sigma_{Q,i}}\right]^{\frac{1}{1-\sigma_{Q,i}}} = 0 \qquad i \in \mathrm{FF}$$

3. Sector-specific energy aggregate:

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

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:

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

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:

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

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 C.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 C.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 C.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 C.4: 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 C.5: 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*) or 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-energy household consumption demand in region *r*
θ_{iCr}^{E}	Share of fossil fuel *i* in household energy consumption in region *r*

Table C.6: Elasticities

η	Transformation between production for the domestic market and production for the export	2
σ_{KLE}	Substitution between energy and value-added in production (except fossil fuels)	0.8
$\sigma_{Q,i}$	Substitution between natural resources and other inputs in fossil fuel production calibrated consistently to exogenous supply elasticities μ_{FF}	μ_{COA}=0.5 μ_{CRU}=1.0 μ_{GAS} =1.0
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	4
σ_{M}	Substitution between imports from different regions	8
σ_{EC}	Substitution between the fossil fuel composite and the non-fossil fuel consumption aggregate in household consumption	0.8
$\sigma_{FF,C}$	Substitution between fossil fuels in household fossil energy consumption	0.3

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

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

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

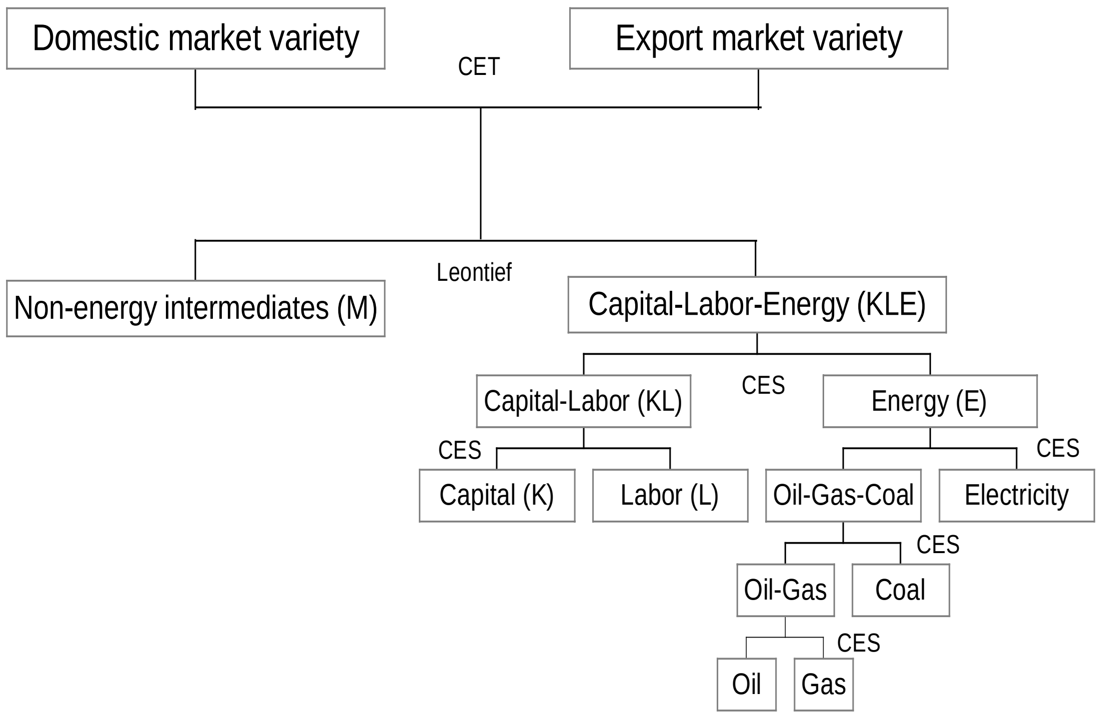


Figure C.2: Nesting in fossil fuel production

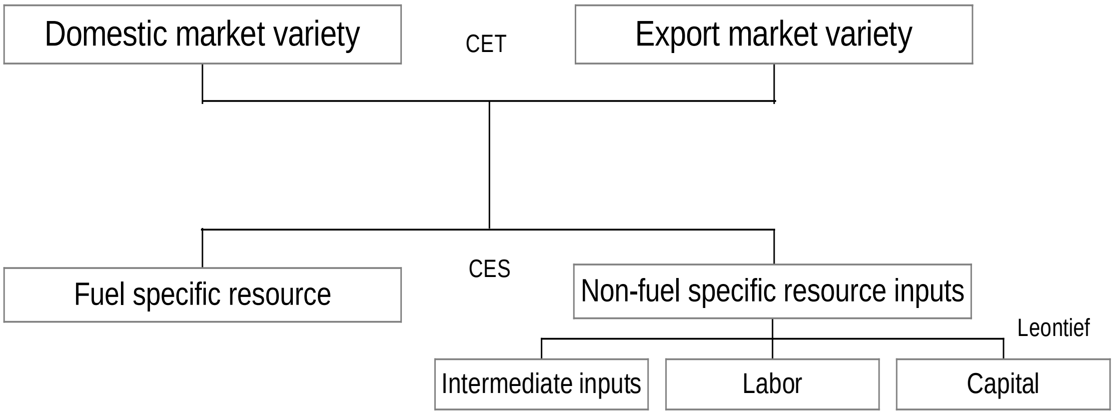


Figure C.3: Nesting in household consumption

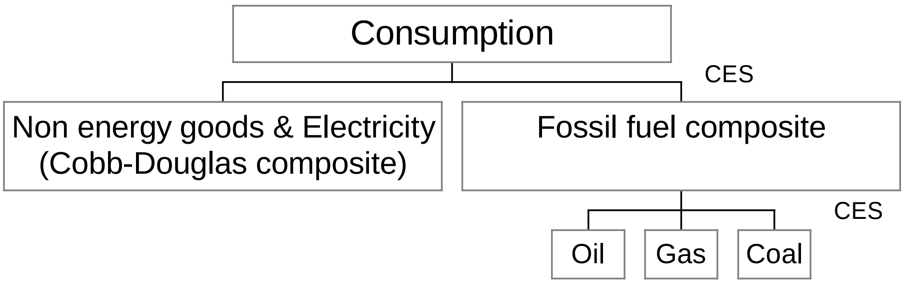
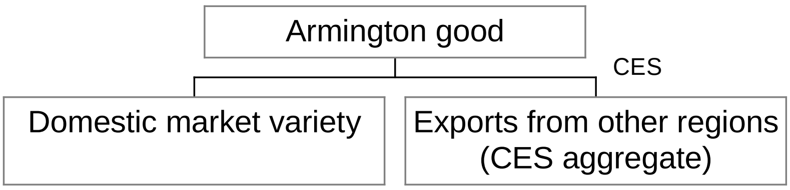


Figure C.4: Nesting in Armington production



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 1997 with OECD/IEA energy statistics for 50 regions and 23 sectors (Rutherford and Paltsev, 2000). Benchmark data determine parameters of the functional forms from a given set of benchmark quantities, prices, and elasticities. Sectors and regions of the original GTAP-EG data set are aggregated according to Tables C.7 and C.8 to yield the model's sectors and regions (see Table 3).

Table C.7: 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 C.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 C.8: Regional aggregation

Regions in GTAP-EG			
ARG	Argentina	MYS	Malaysia
AUS	Australia	NZL	New Zealand
BRA	Brazil	PHL	Philippines
CAM	Central America & 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

Table C.8: continued

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 to GTAP-EG regions

	Industrialized world	
AUN	Australia, New Zealand	AUS, NZL
CAN	Canada	CAN
EUR	OECD Europe (incl. EFTA) and Central and Eastern Associates	CEA, DEU, DNK, EFT, FIN, GBR, REU, SWE, TUR
FSU	Former Soviet Union	FSU
JPN	Japan	JPN
USA	United States	USA
	Developing world	
AFR		MAR, RSA, RSS, SAF
ASI		KOR, LKA, PHL, RAS, ROW, SGP, THA, TWN, VNM
CHN		CHN
IND		IND
MPC		IDN, MEX, MYS, RME, RNF, VEN
MSA		ARG, BRA, CAM, CHL, COL, RAP, RSM

Baseline Projections - Forward Calibration

The magnitude and distribution of abatement costs associated with the implementation of the Kyoto emission constraints crucially depend on the *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 2020 using most recent projections by the International Energy Outlook (DOE, 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 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 to match the exogenous carbon emission profiles The autonomous energy efficiency improvement 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.

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