

## Energy Market Projections and Differentiated Carbon Abatement in the European Union\*

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### 1. Introduction

The Kyoto Protocol documents what many believed to be impossible: negotiators for many of the world's countries agreed on emissions targets for the early part of the 21st century. The protocol commits the Annex I countries to reducing their aggregate CO<sub>2</sub> equivalent emissions by at least 5% below 1990 levels in the period 2008–2012.<sup>1</sup> The agreement reflects wide differences in the willingness to accept emissions constraints: developing countries refused any commitment while the European Union (EU) at the other end agreed to an 8% overall reduction. The burden-sharing negotiations subsequently continued at the EU level when the member states distributed the EU constraint internally. Table 1 shows that the country-specific targets within the EU bubble range from a 28% *reduction* for Luxembourg to a 27% *increase* for Portugal.

Does the EU bubble imply a 'fair' distribution of the burden across EU member states? Economic analysis may inform this debate by translating the emissions constraints into estimates for welfare costs. The cost estimate for a given country will obviously depend on its current economic structure, such as the efficiency of the installed energy-consuming technologies, the fuel mix, and trade relations with other countries. Differences in the starting-point for each country may imply that the same proportional cutback results in high costs in one country and low costs in another.

The expected distribution of costs also depends on differences in the future economic development across countries. That is, the cost estimates will depend on business-as-usual (BAU) projections for GDP, populations, energy efficiency improvements, fuel prices, etc. High economic growth, for example, leads by itself to high energy demands and emissions. This would increase the effective abatement requirement as the Kyoto targets refer to 1990 emissions levels, and higher economic growth will therefore imply higher total abatement costs.

We analyse the agreement on differentiated CO<sub>2</sub> abatement within the EU using the Conventional Wisdom (CW) scenario in European Commission

Table 1. EU member state commitments

Member States	Commitments in accordance with the Kyoto Protocol
Austria	- 13%
Belgium	- 7.5%
Denmark	- 21%
Finland	0%
France	0%
Germany	- 21%
Greece	+ 25%
Ireland	+ 13%
Italy	- 6.5%
Luxembourg	- 28%
Netherlands	- 6%
Portugal	+ 27%
Spain	+ 15%
Sweden	+ 4%
UK	- 12.5%
EU	- 8%

Source: Appendix 1 in EU (1998).

(1996) as the BAU projection. We estimate both the total costs and the distribution of costs across EU member states and evaluate the main assumptions in the BAU projections. Specifically, we focus on the assumptions about non-uniform efficiency improvements and fuel shifting embodied in the CW baseline. Finally, we analyse the consequences of uniform abatement targets across the EU for total costs and the distribution of these costs.

The literature has surprisingly little to say about these issues. Most modellers are typically careful in specifying their BAU assumptions but they rarely report results from sensitivity analyses.

A couple of articles have reported results from the GEM-E3 model of analyses of carbon abatement in 11 EU member states. Conrad and Schmidt (1998a) find that a 10% reduction in CO<sub>2</sub> emissions from the EU implies an overall welfare loss of around 0.24% of GDP when each country has to reduce emissions by 10%. Country-specific welfare effects range from a 0.06% gain in Portugal to a 0.55% loss in Denmark. Permit prices for CO<sub>2</sub> range from US\$10 per tonne in Greece to US\$47 in Denmark (assuming that ECU1 = US\$1). If emissions can be traded between countries, they estimate the permit price to be US\$23 and the overall welfare loss decreases slightly to 0.21%. In a similar analysis, Conrad and Schmidt (1998b) find a double dividend, i.e., 10% lower carbon emissions *and* positive gross welfare effects from the policy, when they recycle permit revenues via a distortionary labour income tax.<sup>2</sup>

Unfortunately, several important differences in model characteristics make it hard to compare the results with the present analysis. First, and most important, none of the articles based on the GEM-E3 model include BAU

projections for GDP, CO<sub>2</sub> emissions, energy prices, etc. Second, the GEM-E3 model includes both a labour–leisure choice and involuntary employment whereas we have a fixed labour supply. Finally, it assumes endogenous balances of trade and exogenous exchange rates. We assume that the balances of trade do not change and let the exchange rates clear the foreign exchange markets.

The present analysis makes three sets of contributions. First, to develop an explicit dynamic model, we extend an existing static, multi-sector model of six EU member states to incorporate representative agents with myopic expectations.<sup>3</sup> Second, we develop a calibration method that allows us to use the CW scenario as our baseline equilibrium. Finally, we use this recursively dynamic model to analyse the EU agreement on differentiated CO<sub>2</sub> abatement.

The following results emerge from our simulations. First, total costs in 2010 for the EU amount to a 0.4% consumption loss and a range of costs for the member states between zero and a loss of 0.7%. CO<sub>2</sub> tax rates vary from US\$22 per tonne CO<sub>2</sub> in Spain to US\$99 in Italy.<sup>4</sup>

Second, the CW baseline embodies significant fuel shifting in electricity production in all countries and high efficiency gains in the Northern European countries. These assumptions imply large decreases in CO<sub>2</sub> intensity and therefore low effective abatement requirements compared with our alternative baseline of uniform growth in energy efficiency of 1% per annum. With the latter baseline, total costs double and the range of costs changes from a low of 0.1% in Spain to a high of 2.2% in Denmark. The uniform baseline lowers the overall level of energy efficiency gains, and CO<sub>2</sub> tax rates therefore increase in all countries. The North experiences the largest decreases in energy efficiency and therefore also the largest increases in CO<sub>2</sub> tax rates.

Finally, we find that uniform abatement targets within the EU have a small impact on total costs, holding total EU abatement constant. The distribution of costs changes, however. Spain and France would suffer large economic losses as their abatement targets change from +15% and 0%, respectively, to –11%.<sup>5</sup> Uniform targets increase costs for Spain and France, while Denmark and Germany reduce their total abatement costs by around 50%. This scenario, although politically unrealistic, illustrates the size of the implicit transfers involved in the burden-sharing negotiations.

Section 2 discusses the CW baseline for future energy markets. Section 3 describes our model and the steps involved in calibrating it to the CW baseline. Section 4 defines our policy scenarios and Section 5 presents the results. Section 6 offers concluding remarks.

## **2. Baseline energy market projections**

EU member states differ significantly with respect to CO<sub>2</sub> characteristics. Table 2 presents summary statistics revealing the main differences. It focuses on the six countries in our model and shows that the selected countries jointly

Table 2. Benchmark data for 1990

A. Summary statistics								
	DE	DK	ES	FR	IT	UK	REU	EU
GDP (% of EU total)	24	2	6	19	15	16	18	100
CO <sub>2</sub> (% of EU total)	32	2	7	12	13	18	17	100
CO <sub>2</sub> (tonnes per capita)	13	11	5	7	7	10	8	9
Electricity (tonnes of CO <sub>2</sub> /GWh)	653	892	429	105	565	686	260	462
B. CO <sub>2</sub> emissions sources (%)								
	DE	DK	ES	FR	IT	UK	REU	EU
Electricity	36	43	31	12	30	38	23	30
Energy production	3	2	6	5	5	5	5	4
Industry	20	11	21	23	20	14	24	20
Transport	17	26	32	34	25	24	26	24
Final demand	24	17	10	26	20	19	22	21
Total	100	100	100	100	100	100	100	100
Regions								
1.	DE	Germany						
2.	DK	Denmark						
3.	ES	Spain						
4.	FR	France						
5.	IT	Italy						
6.	UK	United Kingdom						

Note: The Rest of the European Union (REU) includes Austria, Belgium, Finland, Luxembourg, Greece, Ireland, the Netherlands, Portugal and Sweden.

Source: Calculations based on European Commission (1996; 161–209).

accounted for more than 80% of EU GDP and aggregate EU CO<sub>2</sub> emissions in 1990.<sup>6</sup> The sector contributing most to CO<sub>2</sub> emissions is electricity, whose fuel mix differs significantly across countries. A large share of nuclear-based electricity results in France having a very low CO<sub>2</sub> intensity (tonnes of CO<sub>2</sub> per GWh), whereas large shares of coal-based electricity implies higher intensities in Denmark and Germany. Finally, the rich Northern European countries also have the highest emissions per capita.

What happens to economic growth, energy prices, and CO<sub>2</sub> emissions without climate policy? Cost estimates for the Kyoto commitments crucially depend on answers to this question. CO<sub>2</sub> emissions are directly linked to the combustion of fossil fuels, so it follows that baseline projections of the development of the energy system play a key role in the design of the abatement policies. In particular, projections for energy efficiency improvements and the fuel mix in electricity generation are crucial for the reference level of CO<sub>2</sub> emissions.

Table 3. Conventional Wisdom baseline assumptions

A. Average GDP growth rate (% p.a.)							
	DE	DK	ES	FR	IT	UK	EU
1990–2000	2.8	2.6	2.1	1.9	1.8	1.9	2.1
2000–2010	2.3	2.0	2.7	2.5	2.0	2.1	2.3
B. Average CO <sub>2</sub> growth rate (% p.a.)							
	DE	DK	ES	FR	IT	UK	EU
1990–2000	–0.2	1.9	0.6	0.6	0.9	0.3	0.3
2000–2010	0.1	–0.8	1.4	0.1	0.5	0.2	0.5
C. Implied average improvement in CO <sub>2</sub> intensity (% p.a.)							
	DE	DK	ES	FR	IT	UK	EU
1990–2000	2.9	0.7	1.5	1.3	0.9	1.5	1.8
2000–2010	2.1	2.7	1.3	2.4	1.5	1.9	1.8
D. Average growth rates for fossil fuel inputs to electricity generation (% p.a.)							
	DE	DK	ES	FR	IT	UK	EU
1990–2000							
Coal	–0.8	1.6	–4.9	3.3	6.7	–4.2	–1.0
Oil	8.0	9.3	3.3	–13.1	–0.9	–6.3	–0.1
Gas	4.2	25.4	25.8	6.5	2.2	31.3	8.3
2000–2010							
Coal	–0.5	–3.4	2.1	–11.9	–0.8	–6.0	–1.2
Oil	–1.5	–5.1	–1.2	–14.3	–5.4	3.4	–2.2
Gas	6.0	7.3	7.9	10.9	8.5	6.1	6.6

Source: Calculations based on European Commission (1996; 161–209).

The CW scenario in European Commission (1996) suggests how energy markets in Europe might evolve if current policies remain in place.<sup>7</sup> The assumptions of the CW scenario include smooth increases in world energy prices, no changes in current energy taxes, limited penetration of more efficient supply technologies, and no changes in energy market regulation. Renewable, CO<sub>2</sub> free, energy production increases its share in total energy supply but fossil fuels continue to be the main source of energy. Gas and oil consumption increase, whereas the use of nuclear fuels and coal slowly decreases.

Table 3 summarizes the CW baseline with respect to economic growth, the development of CO<sub>2</sub> emissions, and the fossil fuel mix in thermal electricity generation. France and the CO<sub>2</sub>-intensive Northern European countries experience the largest decreases in the CO<sub>2</sub> intensity. Overall, the CW baseline

Table 4. Sectors in the model

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Production sectors (Eurostat's R59 code in brackets):

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1. Coal (031,033)
2. Crude oil (071)
3. Refined oil (073)
4. Natural and manufactured gases (075,098)
5. Electricity and steam (097,099)
6. Agriculture (010)
7. Iron and steel (135,136)
8. Chemical products (170)
9. Non-ferrous metals (137)
10. Non-metallic minerals (151,153,155,157)
11. Machinery (190,210,230,250)
12. Transport equipment (270,290)
13. Paper pulp and printing (471,473)
14. Wood and wood products (450)
15. Food processing beverages and tobacco (310,330,350,370,390)
16. Textiles and leather (410,430)
17. Transport (611,613,617,631,633,650)
18. Other industries (095,490,510,530,550,570,590,670,690,710,730,750,770,790,810,850,890,930)

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embodies a strong decoupling of growth in GDP and CO<sub>2</sub> emissions, as summarized by an average change in the CO<sub>2</sub>-intensity of almost 2%. Fuel shifting and significant efficiency improvements account for this result. Section D in Table 3 focuses on the electricity sector where the emissions intensity decreases significantly due to fuel shifting from coal to gas.

### 3. Analytical framework and baseline calibration

This section presents the main characteristics of a recursively dynamic multi-sector model of the six EU countries. We also discuss the representation of the CW scenario as our baseline and the subsequent sensitivity analysis of the BAU assumptions.

The model is a dynamic extension of a previous static model designed to investigate the economic implications of alternative CO<sub>2</sub> abatement strategies for the European Union.<sup>8</sup> Table 4 gives an overview of the sectoral disaggregation of the current model for the six regions in Tables 2 and 3. The choice of sectors and regions captures key dimensions in the analysis of CO<sub>2</sub> abatement such as differences in CO<sub>2</sub> intensity across sectors, energy goods, and bilateral trade. Appendix A provides an algebraic documentation of the model.

We have developed an explicitly dynamic model to incorporate the time paths for GDP, CO<sub>2</sub> emissions, energy prices, etc., for the CW scenario. We assume constant, region-specific marginal propensities to save consistent with a growth rate of 2% per year in all countries. The path for the economy is represented by

a set of connected equilibria where the current period's saving augments capital stocks in the next period. Consumers allocate income between present and future consumption subject to a fixed marginal propensity to save and investment adjusts passively to savings. The intra-period model corresponds to the previous static model. Base year data determine the parameters of the functional forms from a given set of quantities, prices and benchmark elasticities.

A simple calibration of the model along the time path would typically involve calibration to a steady state where all physical quantities (including CO<sub>2</sub> emissions) grow at an exogenous uniform rate while relative prices remain unchanged. The virtue of a steady-state baseline is that it provides a transparent reference path for the evaluation of policy interference: any structural change in the counterfactual can be attributed to the new policy.

In the present analysis we want to incorporate exogenous information from the CW baseline on non-uniform growth rates in GDP, fossil fuel production, fuel mixes in electricity generation, changes in world market energy prices and CO<sub>2</sub> emissions profiles. The calibration procedure involves two steps.<sup>9</sup> First, we scale factor endowments, fuel demands in electricity production and world market energy prices. Second, we incorporate autonomous energy efficiency improvements (AEEI) to match the aggregate emissions profiles. AEEI represents energy efficiency improvements *in addition* to energy demand reductions caused by changes in energy prices. The European Commission (1996) mentions research or changes in public standards as sources of efficiency improvements.

After the calibration the model represents the CW baseline as an equilibrium solution. Figure 1 shows the CW CO<sub>2</sub> emissions profile with an alternative BAU path labelled LOW\_AEEI. The latter deviates from CW only with respect to the assumption about AEEI and exogenous fuel shifting in the electricity sector. In the LOW\_AEEI baseline we solve the model with all AEEI equal to 1% p.a. and let relative prices determine the fuel mix in the electricity sector.

Table 5 shows that aggregate CO<sub>2</sub> emissions in 2010 exceed the 1990 level by 6% in the CW baseline and 20% in the LOW\_AEEI baseline. Two factors explain most of this difference. First, the CW baseline implies more fuel shifting from coal to gas in the electricity sector than the model can explain with changes in relative prices. Second, AEEI exceeds 1% p.a. in many cases in the CW baseline, and in particular Germany and Denmark are expected to experience large energy efficiency improvements.<sup>10</sup>

We do not regard the LOW\_AEEI baseline as more realistic than the CW baseline that is based on a compilation of detailed country studies. Rather we think of it as a sensitivity analysis that illustrates the implications of the CW assumptions about relatively high values for AEEI and fuel shifting in electricity generation.

#### 4. Scenario definitions

Our numerical analysis distinguishes three CO<sub>2</sub> abatement scenarios: KYOTO, UNIFORM, and HIGH\_BAU. The KYOTO scenario implements the EU

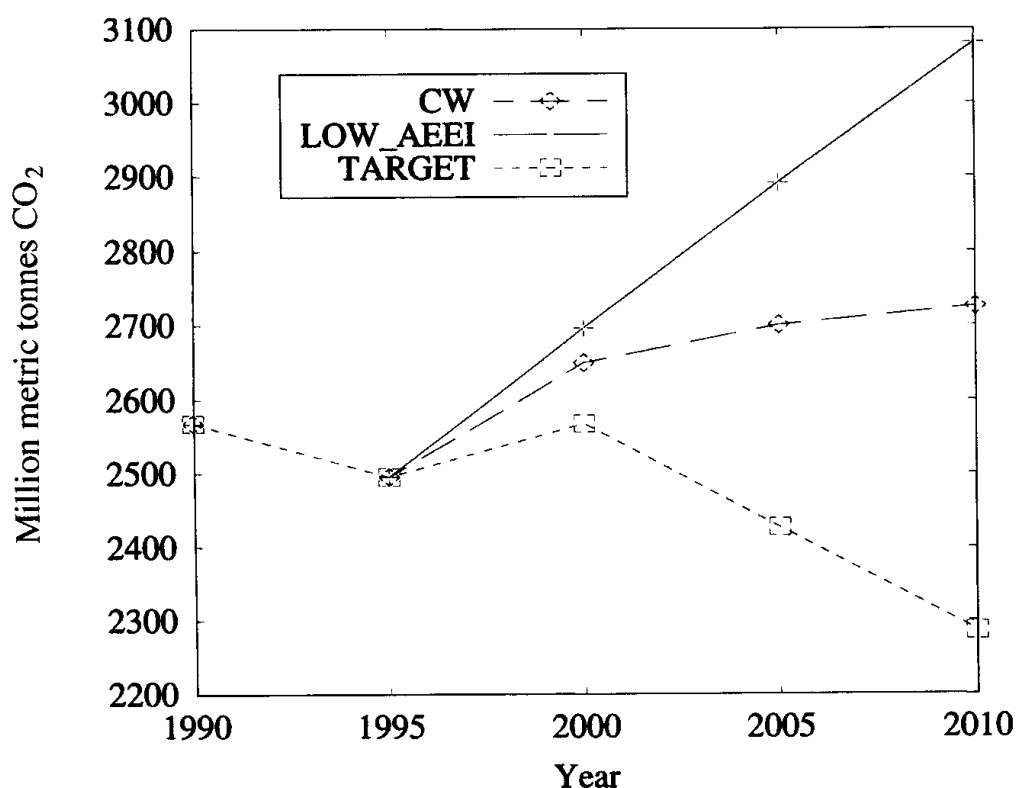


Figure 1. Emissions profiles.

Table 5. Change in emissions in 2010

	Relative to 1990 emissions			Relative to BAU emissions in 2010		
	KYOTO	CW	LOW_AEEI	KYOTO	UNIFORM	HIGH_BAU
DE	-21%	-1%	18%	-21%	-10%	-33%
DK	-21%	12%	45%	-30%	-21%	-45%
ES	15%	22%	28%	-6%	-27%	-10%
FR	0%	7%	19%	-6%	-17%	-16%
IT	-6.5%	15%	15%	-18%	-22%	-18%
UK	-12.5%	5%	22%	-17%	-15%	-28%
EU	-11%	6%	20%	-16%	-16%	-26%

Source: European Commission [1996; 161–209] and own calculations.

agreement on differentiated emissions reductions that distributes the 8% Kyoto commitment by the EU across member states.<sup>11</sup> The KYOTO scenario, which employs the CW baseline as the BAU, represents our base case.

The differentiated cutbacks amount to an average reduction of 11% for the six countries in our model. The UNIFORM scenario requires all six countries to reduce emissions uniformly by 11% and it also uses the CW baseline. This



scenario allows us to analyse the implications of the differentiated cutbacks, holding total EU emissions constant.

In the HIGH\_BAU scenario we apply the differentiated cutbacks used in the KYOTO scenario but employ different BAU assumptions: All AEEI equal 1% p.a. and relative prices determine the fuel mix in electricity production, i.e., the LOW\_AEEI baseline.

The last three columns in Table 5 show the effective abatement requirements in 2010 in the three scenarios. As expected, the choice of baseline has a considerable impact on the required abatement effort.

Several characteristics are common to all three scenarios. First, all scenarios result in the same aggregate CO<sub>2</sub> abatement for the six EU countries in the model. We ignore the issue of carbon leakage and we thus assume that the EU policies do not lead to higher emissions outside the EU. This allows us to compare the results without considering the benefits from CO<sub>2</sub> abatement, i.e., we only consider the gross costs.

Second, we use the same cutback profile for aggregate EU emissions in all scenarios. Specifically, we assume a stabilization of aggregate emissions in the year 2000 at 1990 levels and a linear cutback between 2000 and 2010. In other words, all countries have to meet half their 2010 commitments by 2005.

Third, we do not allow for trade in emissions across countries. Emissions can be traded across sectors within a given country, but all emissions reductions must take place domestically and no emissions can be purchased abroad.

Fourth, we incorporate the emissions constraints as a resource constraint in the model where we interpret the shadow price on the constraint as the CO<sub>2</sub> tax rate. The representative consumer in each region collects all the revenue, and the provision of public goods stays constant.

The model solves for counterfactual equilibriums in five-year steps starting in the year 2000. We report consumption losses and CO<sub>2</sub> tax rates in Figures 2–5. Consumption losses are calculated as the percentage change in final consumption relative to the relevant baseline and CO<sub>2</sub> tax rates (marginal abatement costs) are reported in US dollars at constant 1990 prices per metric tonne of CO<sub>2</sub>.

## **5. Results**

The effective emissions targets provide the starting-point for the interpretation of the results (see Table 5) and we begin with our base case, the KYOTO scenario. Figure 2 shows that the high-abatement countries, Denmark, Germany, Italy and the UK, face high carbon taxes whereas the low targets for France and Spain require relatively low tax rates. The stabilization of Germany's emissions in the year 2000 does not require any carbon tax as the unification caused a significant drop in emissions from 1990 to 1995.

The carbon taxes cause efficiency losses, and Figure 3 summarizes the results

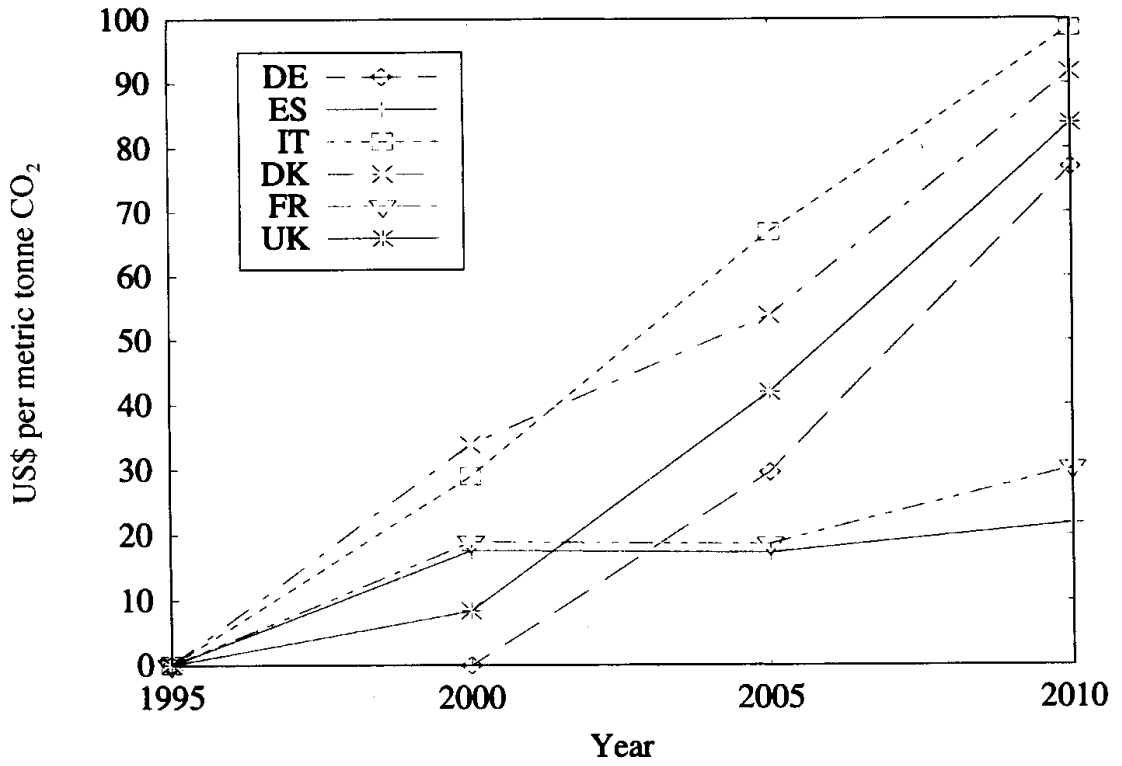


Figure 2. Carbon tax rates in the KYOTO scenario.

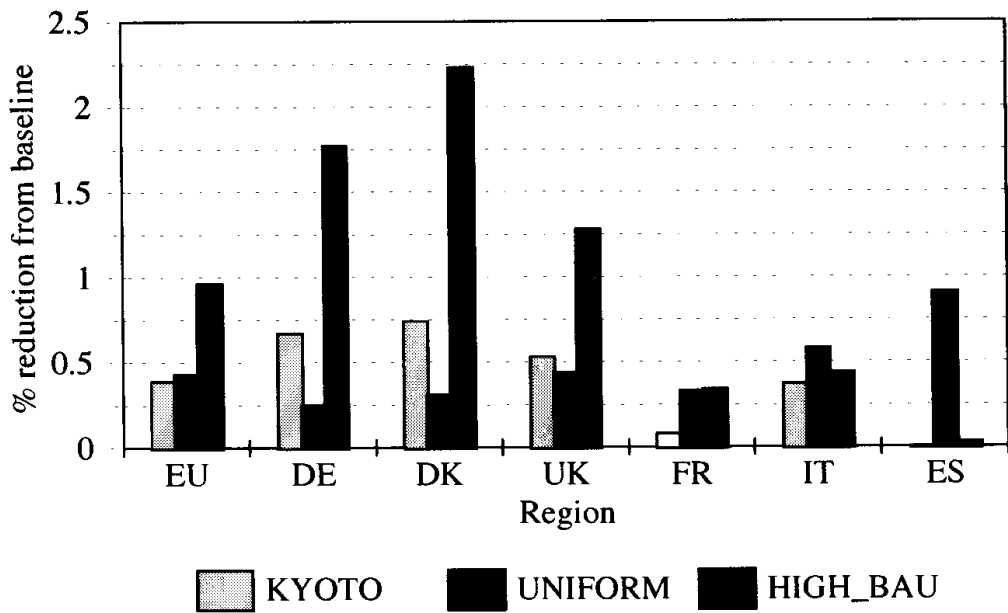


Figure 3. Consumption losses in 2010.

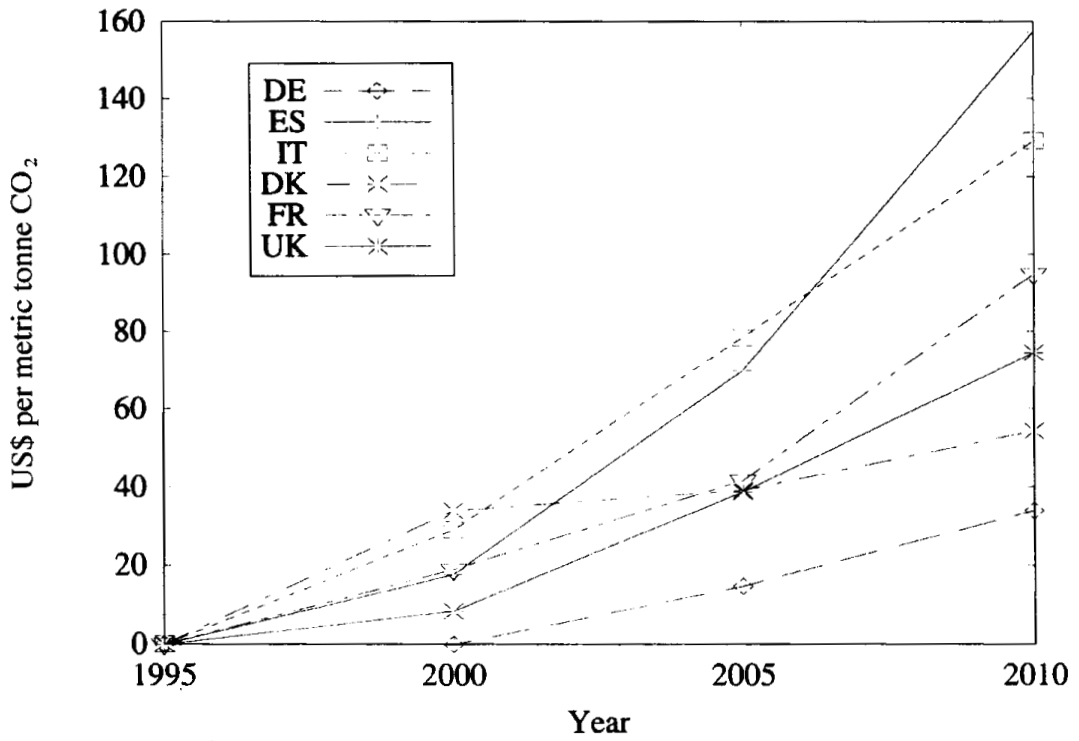


Figure 4. Carbon tax rates in the UNIFORM scenario.

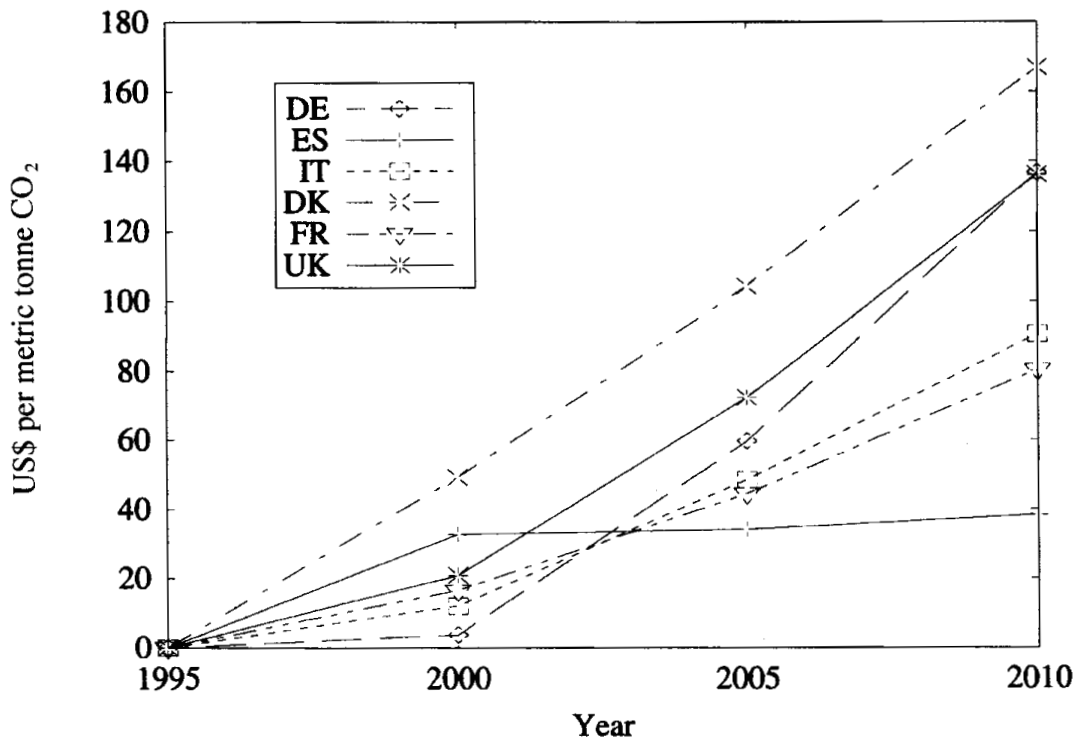


Figure 5. Carbon tax rates in the HIGH\_BAU scenario.

for consumption losses in 2010. Overall, the KYOTO scenario implies a total consumption loss of 0.4% in 2010 and the distribution of consumption losses reflects the differences in tax rates as explained above. The high-abatement countries Germany and Denmark also bear the highest consumption losses while France and Spain meet their targets at very low cost. Two effects work in opposite directions to produce the negligible consumption loss for Spain. First, the low tax rate induces a low efficiency cost. Second, Spain experiences a gain as its production becomes more competitive compared with its EU competitors because tax rates are much higher in the rest of the EU.

All three Southern countries (Spain, Italy and France) face higher targets in the UNIFORM scenario compared with the KYOTO scenario, whereas the Northern countries' emissions constraints become less binding. This implies a significantly different pattern of carbon taxes as shown in Figure 4. Low efficiency gains and relatively little fuel shifting in the CW baseline imply that the uniform targets result in relatively high effective targets in the Southern countries. These countries therefore experience the highest tax rates.

Figure 3 shows that total EU costs increase marginally in the UNIFORM scenario, but the cost distribution changes dramatically. Compared to the KYOTO scenario, the costs for Denmark and Germany decrease by around 50% whereas the costs increase in all Southern countries. Spain jumps from virtually zero costs to a 0.9% consumption loss. While this scenario may be politically irrelevant, it shows the implicit transfers involved in the negotiations about the EU bubble. Total EU emissions are identical in the KYOTO and the UNIFORM scenarios but the distribution of emissions allowance differs. The larger the allowance, the lower the carbon tax rate and the lower the efficiency cost.

Both the KYOTO and the UNIFORM scenarios use the CW baseline. The LOW\_AEEI baseline in Figure 1 shows that baseline emissions exceed CW emissions by 14% of 1990 emissions when AEEI equals 1% p.a. and relative prices determine the fuel mix in electricity production. The last column in Table 5 shows that the EU commitment in Kyoto now requires effective total cutbacks of 26% compared with the LOW\_AEEI baseline. The effective targets increase for all countries, and the Northern countries experience the highest increases.

Figure 5 shows, as expected, that higher carbon taxes follow the more stringent targets in the HIGH\_BAU scenario. Tax rates increase between 50 and 100% for all countries except Italy.<sup>12</sup> The higher rates cause higher consumption losses in all countries and increase the range of costs from 0.1% in Spain to 2.2% in Denmark. Put differently, if the optimistic CW baseline fails to materialize and future European energy markets develop more uniformly, the differentiated targets will imply a less equitable distribution of abatement costs.

Finally, we relax the assumption about no trade in emissions across countries. Specifically, we assume that all six countries can trade emissions freely such that the same carbon tax rate applies in all countries. The quantitative effects

of this change turn out to be small and we thus conclude that our results are robust with respect to the assumption about emissions trading.

In our model, trade in emissions leads to equalization of the domestic carbon tax rates and this influences the results via two channels: the distortionary effects of carbon taxes change and the values of the emissions endowments change. Countries that previously had carbon tax rates below the new common tax rate will experience higher distortionary costs from higher carbon tax rates but they will also find their emissions endowments more valuable. Conversely, countries with high carbon tax rates will have lower distortionary costs but also lower carbon tax revenues. Emissions trading may also change the international incidence of carbon taxes as the burden of the taxes in a given country now gets shifted differently to foreign and domestic agents.

We use the model to trace all these effects, and the main results can be summarized as follows.<sup>13</sup> First, some countries gain slightly, others experience small losses and the overall EU costs decrease marginally. That is, trading *within* the EU implies small total cost savings. Intuitively, the differences in carbon tax rates before we allow for trading are significant but not large, and this effectively limits the extent of emissions trading. Spain, a net exporter, and Germany, a net importer, gain most from emissions trading. Second, we also conclude that our results regarding energy market projections are robust. We find that the effects of changing projections are similar to the no-trading case, although mostly the effects are quantitatively smaller. Finally, uniform abatement targets continue to show large implicit transfers from Northern European member states to Southern member states. This result holds although the differences in consumption losses decrease between differentiated and uniform abatement targets.

## **6. Concluding remarks**

Burden sharing dominates the climate policy negotiations since the participating countries must view the expected distribution of costs as 'fair' in order for them to be politically acceptable. Negotiators point both to the countries' current economic structure *and* to the projections for the future economic development when they propose 'fair' abatement targets.

We have analysed the EU agreement on differentiated greenhouse gas abatement with a particular focus on the role of baseline projections for future energy markets. We used a dynamic multi-sector, multi-region general equilibrium model for the EU. The following insights emerge from our policy simulations:

- (1) The overall costs of the EU bubble following its Kyoto commitment are low when we use the CW scenario provided by the European Commission as the baseline. The range of costs across member states is narrow, and the

necessary CO<sub>2</sub> taxes in the year 2010 are below US\$100 per tonne CO<sub>2</sub> in all countries.

- (2) The CW baseline implies significant fuel shifting in electricity generation and large energy-efficiency improvements by historical standards. If the projected, strong decoupling of GDP growth and CO<sub>2</sub> fails to materialize, both the overall CO<sub>2</sub> abatement costs and the range of costs across member states may increase significantly.
- (3) Uniform abatement hardly increases total costs but it changes the cost distribution between countries considerably. We show that the EU bubble implicitly involves large economic transfers from the Northern European member states to the Southern European member states. This may be consistent with a higher willingness to pay for emissions reductions in the Northern countries.

Finally, we close with a caveat. Our model captures important aspects of bilateral trade and energy consumption in the EU. It is nonetheless a crude approximation of the real world's technologies, preferences, factor endowments, etc., and we therefore caution against too literal an interpretation of the numerical results.

## Notes

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1. Article 3 in United Nations (1997). The group of Annex I countries consists of developed economies plus economies in transition, listed in Annex I of United Nations (1992).
2. See Capros et al. (1998) for more results from the GEM-E3 model.
3. The model includes three Northern EU countries (Denmark, Germany and the UK) and three Southern EU countries (France, Italy and Spain).
4. We recycle carbon tax revenues via lump-sum transfers to the representative agents in the model. Also, we assume that emissions cannot be traded across countries.
5. The EU targets for the six countries amount to an average emissions cutback of 11%.
6. The six selected countries also emit roughly 80% of EU emissions in 2010 in the projections reported below.
7. See European Commission (1996; pp. 48–54) for the complete description of this scenario.
8. See Böhringer, Ferris and Rutherford (1998) for an algebraic formulation of the static model, and Böhringer, Harrison and Rutherford (1998) for an application of the static model to carbon abatement and burden sharing within the EU.
9. See Appendix B for details of the calibration procedure.
10. A poll of 22 experts reported in Manne and Richels (1994) results in an average AEEI value of 0.7% p.a.
11. See EU (1998).

12. Italy's CW baseline emissions grow relatively slowly because of the absence of fuel-shifting in the electricity sector and low efficiency improvements.
13. The tables with results are available from the authors.

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## Appendix A

This appendix provides an algebraic summary of the equilibrium conditions for the model. First, we present the main assumptions of the model and introduce notation. We then present the algebraic model.

Nested constant elasticity of substitution (CES) functions characterize the use of inputs in production, and all production exhibits non-increasing returns to scale. Goods are produced with capital, labour, energy and materials, and all sectors produce a single good. We therefore use 'goods' and 'sectors' interchangeably. Firms behave competitively and all markets are perfectly competitive.

A representative agent (RA) in each region is endowed with three primary factors: natural resources (used for fossil fuel production), labor and initial stock of capital. Nested CES functions characterize consumption by the RA (final demand) and the RA has myopic expectations, i.e., he is not forward-looking. The supplies of labour and natural resources are exogenous, and labour and capital can move freely across sectors within each region but cannot move between regions. Natural resources are sector specific.

All goods, except coal, crude oil and gas, are differentiated by region of origin. Constant elasticity of transformation functions 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).

The rest of the world is represented with horizontal export demand and import supply schedules, i.e., the EU regions behave as a small open economy. The balance of payments for each region with respect to the rest of the world is exogenous.

A constant marginal propensity to save characterizes the RA's allocation of income between savings, i.e., investments and current consumption. Investments begin to provide capital services one period after installation, and the capital stock depreciates at a constant rate. Growth augments the labour endowment at a constant rate.

Finally, lump-sum transfers finance the exogenous government demands, and the government in each region transfers all carbon tax revenues to the RA in the region.

The myopic expectations imply that the economies effectively reduce to a set of connected equilibria, where the current period's investments augment the capital stock in the next period. That is, all equilibrium conditions are strictly intra-period and we can thus omit time indices without loss of generality.

We characterize the model with two classes of equilibrium conditions: zero profit conditions and market clearance conditions. The former determines activity levels and the latter determines price levels. Tables A.1 and A.2 show the activity and the price levels in the model and Table A.3 explains the set notation.

The algebraic exposition of the model begins with the profit functions. We then derive the market clearance conditions by exploiting Shephard's lemma:

Table A.1. 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 in good $i$ and region $r$
$A_{dir}$	Armington aggregate for demand category $d$ of good $i$ in region $r$
$I_r$	Aggregate investment in region $r$
$G_r$	Aggregate public output in region $r$
$C_r$	Aggregate household consumption in region $r$
$D_r$	Aggregate household energy consumption in region $r$



Table A.2. Price variables

$p_{ir}$	Output price of good $i$ produced in region $r$
$p_{ir}^E$	Price of aggregate energy in sector $i$ and region $r$
$p_{ir}^M$	Import price aggregate for good $i$ imported to region $r$
$p_{dir}^A$	Price of Armington aggregate for demand category $d$ of good $i$ in region $r$
$p_r^I$	Price of investment demand in region $r$
$p_r^G$	Price of government demand in region $r$
$p_r^C$	Price of aggregate household consumption in region $r$
$p_r^{EC}$	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 $r$ ( $i \in FF$ )
$p^w$	Real exchange rate with the rest of the world
$t_r^c$	Carbon tax in region $r$

Table A.3. Sets

$i$	Sectors and goods
$j$	Aliased with $i$
$r$	EU 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, refined oil and gas
$d$	Demand categories: $Y$ = intermediate, $C$ = household, and $I$ = investment

differentiation of the profit functions with respect to input and output prices yields compensated demand and supply functions. The exposition and our empirical implementation uses calibrated CES functions as the key element. Tables A.4–A.6 explain the notation for the calibrated model parameters.

Zero profit conditions:

1. Production of goods except fossil fuels:

$$\begin{aligned} \Pi_{ir}^Y = & \left( \sum_s \theta_{irs}^X p_{is}^{1-\eta} + \theta_w^X p^w{}^{1-\eta} \right)^{1/(1-\eta)} \sum_{j \notin E} \theta_{jir} p_{Yjr}^A - \theta_{ir}^{KLE} \\ & \times [\theta_{ir}^E p_{ir}^{E1-\sigma_{KLE}} + (1 - \theta_{ir}^E)(w_r^{\alpha_{ir}^L} v_r^{1-\alpha_{ir}^L})^{1-\sigma_{KLE}}]^{1/(1-\sigma_{KLE})} = 0, \quad i \in FF \end{aligned}$$

2. Production of fossil fuels:

$$\begin{aligned} \Pi_{ir}^Y = & p^w - \left[ \theta_{ir}^Q q_{ir}^{1-\sigma_Q} + (1 - \theta_{ir}^Q) \right. \\ & \left. \times \left( \delta_{ir}^L w_r + \delta_{ir}^K v_r + \sum_j \theta_{jir}^{FF} p_{Yjr}^A \right)^{1-\sigma_Q} \right]^{1/(1-\sigma_Q)} = 0, \quad i \in FF \end{aligned}$$

3. Sector-specific energy aggregate:

$$\begin{aligned} \Pi_{ir}^E = p_{ir}^E - \left\{ \theta_{ir}^{CO} p_{\{Y,COA,r\}}^{A^{1-\sigma_{CO}}} + (1 - \theta_{ir}^{CO}) \left[ \theta_{ir}^{EL} p_{\{Y,ELE,r\}}^{A^{1-\sigma_{EL}}} \right. \right. \\ \left. \left. + (1 - \theta_{ir}^{EL}) \left( \prod_{j \in LQ} p_{Yjr}^{A^{1-\sigma_{EL}}} \right)^{1-\sigma_{EL}} \right]^{(1-\sigma_{CO})/(1-\sigma_{EL})} \right\}^{1/(1-\sigma_{CO})} = 0, \quad i \notin FF \end{aligned}$$

4. Armington aggregate except fossil fuels:

$$\Pi_{dir}^A = p_{dir}^A - \{ [\theta_{dir}^A p_{ir}^{1-\sigma_A} + (1 - \theta_{dir}^A) p_{ir}^{M^{1-\sigma_A}}]^{1/(1-\sigma_A)} + t_r^c a_{dir}^c \} = 0, \quad i \notin FF$$

5. Armington aggregate for fossil fuels

$$\Pi_{dir}^A = p_{dir}^A - (p^w + t_r^c a_{dir}^c) = 0, \quad i \in FF$$

6. Aggregate imports across import regions except fossil fuels:

$$\Pi_{ir}^M = p_{ir}^M - \left( \theta_{ir}^W p^{w^{1-\sigma_M}} + \sum_s \theta_{isr}^M p_{is}^{1-\sigma_M} \right)^{1/(1-\sigma_M)} = 0, \quad i \notin FF$$

7. Investment:

$$\Pi_r^I = p_r^I - \sum_i \theta_{ir}^I p_{ir}^A = 0$$

8. Public good production:

$$\Pi_r^G = p_r^G - \sum_i \theta_{ir}^G p_{ir}^A = 0$$

9. Household consumption demand:

$$\Pi_r^C = p_r^C - \left[ \lambda_r^E p_r^{EC^{1-\sigma_{EC}}} + (1 - \lambda_r^E) \left( \prod_{i \in EG} p_{\{C,i,r\}}^{A^{1-\sigma_{EC}}} \right)^{1-\sigma_{EC}} \right]^{1/(1-\sigma_{EC})} = 0$$

10. Household energy demand:

$$\begin{aligned} \Pi_r^{EC} = p_r^{EC} \left\{ \lambda_r^{EL} p_{\{C,ELE,r\}}^{1-\sigma_{EL}} + (1 - \lambda_r^{EL}) \right. \\ \left. \times \left[ \left( \sum_{i \in EG \setminus \{ELE\}} \lambda_{ir}^E p_{\{C,i,r\}}^{A^{1-\sigma_{NE}}} \right)^{1/(1-\sigma_{NE})} \right]^{1-\sigma_{EL}} \right\}^{1/(1-\sigma_{EL})} = 0 \end{aligned}$$

Market Clearance Conditions

11. Labour:

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

12. Capital:

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

13. Natural resources:

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

14. Output except fossil fuels:

$$Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}} = \sum_{d,j} A_{dir} \frac{\partial \Pi_{dir}^A}{\partial p_{ir}} + \sum_s M_{is} \frac{\partial \Pi_{is}^M}{\partial p_{ir}}, \quad i \notin FF$$

15. Sector-specific energy aggregate:

$$E_{ir} = Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p_{ir}^E}$$

16. Import aggregate except fossil fuels:

$$M_{ir} = \sum_d A_{dir} \frac{\partial \Pi_{dir}^A}{\partial p_{ir}^M}, \quad i \notin FF$$

17. Armington aggregate:

$$A_{dir} = \sum_j Y_{jr} \frac{\partial \Pi_{jr}^Y}{\partial p_{dir}^A} + C_r \frac{\partial \Pi_r^C}{\partial p_{dir}^A} + I_r \frac{\partial \Pi_r^I}{\partial p_{dir}^A} + G_r \frac{\partial \Pi_r^G}{\partial p_{dir}^A}$$

18. Household consumption:

$$p_r^C C_r = (1 - \mu_r) \left( w_r \bar{L}_r + v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} + t_r^c \bar{Z}_r - p_r^G \bar{G}_r - p^w \bar{B}_r \right)$$

19. Savings:

$$p_r^I I_r = \mu_r \left( w_r \bar{L}_r + v_r \bar{K}_r + \sum_{j \in FF} q_{jr} \bar{Q}_{jr} + t_r^c \bar{Z}_r - p_r^G \bar{G}_r - p^w \bar{B}_r \right)$$

20. Aggregate household energy consumption:

$$D_r = C_r \frac{\partial \Pi_r^C}{\partial p_r^{EC}}$$

21. Balance of payments:

$$\sum_i Y_{ir} \frac{\partial \Pi_{ir}^Y}{\partial p^w} + \sum_r \bar{B}_r = \sum_{i \in FF} \frac{\partial \Pi_{ir}^M}{\partial p^w} + \sum_{i \in FF,d} \frac{\partial \Pi_{dir}^A}{\partial p^w}$$

22. CO<sub>2</sub> emissions:

$$\bar{Z}_r = \sum_{d,i} A_{dir} \frac{\partial \Pi_{dir}^A}{\partial p_r^c}$$

23. Government output:

$$\bar{G}_r = G_r$$

Table A.4. Cost shares

$\theta_{irs}^X$	Share of exports from sector $i$ in region $r$ to region $s$ ( $i \in FF$ )
$\theta_{ir}^W$	Share of exports from sector $i$ in region $r$ to the rest of the world ( $i \in FF$ )
$\alpha_{ir}^L$	Share of labour in value added in sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{jir}$	Share of intermediate good $j$ in sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{ir}^{KLE}$	Share of KLE aggregate in sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{ir}^E$	Share of energy in the KLE aggregate of sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{ir}^Q$	Share of natural resources in sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{ir}^{FF}$	Share of intermediate good $j$ in sector $i$ of region $r$ ( $i \in FF$ )
$\delta_{ir}^L$	Share of labour in sector $i$ and region $r$ ( $i \in FF$ )
$\delta_{ir}^K$	Share of capital in sector $i$ and region $r$ ( $i \in FF$ )
$\theta_{ir}^{CO}$	Share of coal in energy demand by sector $i$ in region $r$ ( $i \in FF$ )
$\theta_{ir}^{EL}$	Share of electricity in non-coal energy demand by sector $i$ in region $r$ ( $i \in FF$ )
$\beta_{jir}$	Share of fossil fuel $j$ in energy demand by sector $j$ in region $r$ ( $i \in FF, j \in LQ$ )
$\theta_{isr}^M$	Share of imports of good $i$ from region $s$ to region $r$ ( $i \in FF$ )
$\theta_{dir}^A$	Share of domestic variety $i$ in Armington aggregate for demand category $d$ for good $i$ in region $r$
$\theta_{ir}^I$	Share of good $i$ in investment in region $r$
$\theta_{ir}^G$	Share of good $i$ in government demand in region $r$
$\lambda_{ir}^{EC}$	Share of energy in aggregate household consumption in region $r$
$\gamma_{ir}$	Share of non-energy good $i$ in non-energy household consumption demand in region $r$
$\lambda_{ir}^{EL}$	Share of electricity in aggregate household energy consumption in region $r$
$\lambda_{ir}^E$	Share of non-electric energy good $i$ in the non-electric household energy consumption in region $r$
$\mu_r$	Marginal propensity to save in region $r$

Table A.5. Endowments and emissions coefficients

$\alpha_{djr}^c$	Carbon emissions coefficient for fossil fuel $j$ in demand category $d$ of region $r$ ( $j \in FF$ )
$\overline{L}_r$	Aggregate labour endowment in region $r$
$\overline{K}_r$	Aggregate capital endowment in region $r$
$\overline{Q}_{ir}$	Endowment of natural resource $i$ in region $r$ ( $i \in FF$ )
$\overline{G}_r$	Aggregate government demand in region $r$
$\overline{B}_r$	Balance of payment surplus in region $r$
$\overline{Z}_r$	Endowment of carbon emissions rights in region $r$

Table A.6. Elasticities

$\eta$	Transformation between production for the domestic and export markets	4
$\sigma_{KLE}$	Substitution between energy and value added in non-fossil fuel production	0.3
$\sigma_Q$	Substitution between natural resources and other inputs in fossil fuel production	
$\rho$	Supply in fossil fuel production	1
$\sigma_{CO}$	Substitution between coal and the non-coal energy in non-fossil fuel production	0.5
$\sigma_{EL}$	Substitution between electricity and the non-coal fossil fuels in non-fossil fuel production	0.3
$\sigma_M$	Substitution between imports from different regions	8
$\sigma_A$	Substitution between the import aggregate and the domestic good	4
$\sigma_{EC}$	Substitution between energy and non-energy in household consumption	0.3
$\sigma_{EL}$	Substitution between electricity and the non-electric energy in household energy consumption	0.3
$\sigma_{NE}$	Substitution between non-electric energy in household energy consumption	0.5

## **Appendix B**

This appendix describes the calibration of our model to the CW baseline. In two steps, we incorporate exogenous information on non-uniform growth rates in GDP, fossil fuel production, fuel mixes in electricity generation, changes in world market energy prices and CO<sub>2</sub> emissions profiles.

First, we fix the time profile of fossil-fuel supplies from the EU 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 emissions profile from the supply side (except the effects of imported fuels). On the demand side, we incorporate AEEI on the energy demands by consumers and production activities. We also incorporate exogenous fuel shifting in the electricity sector, and exogenous, region-specific GDP growth rates determine the size of labour endowments. Finally, we adjust import demand and export supply functions with respect to the rest of the world to account for exogenous changes in world market energy prices. We solve the model with these changes in parameter values and obtain country-specific estimates for CO<sub>2</sub> emissions.

These estimates deviate from the CO<sub>2</sub> emissions profile in the CW baseline by changes in the fossil fuel supplies from the rest of the world. We therefore include a second step in the calibration procedure where we scale the non-electric AEEI factors to reduce energy demands and, hence, CO<sub>2</sub> emissions. The scaling takes place country by country to match the model as closely as possible to the CW emissions profiles. We solve the model again to verify that it represents the CW baseline as an equilibrium solution. Finally, we use the equilibrium prices to calibrate the fossil fuel production functions to a price elasticity of supply equal to one.