Sharing the Burden of Carbon Abatement in the European Union

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Summary:
We evaluate the welfare implications of alternative ways in which the EU could distribute its aggregate emission reduction commitment under the Kyoto Protocol across member states. An endogenous burden sharing calculation, in which the welfare costs across member states are equalized, differs substantially from uniform proportional cutbacks as well as the specific burden sharing rule actually adopted by the EU.

Keywords: Carbon Abatement, EU Climate Policy, Burden Sharing

1 Introduction

The Third Conference of the Parties (COP3) in Kyoto, 1997, produced a climate protocol which entails quantified emission limitations for developed countries (United Nations [1997]). Within the Kyoto Protocol the European Union (EU) is committed to cut back its greenhouse gas emissions by 8% on average during the period 2008-2012 as compared to 1990 emission levels. This target will be binding on the member states of the EU as a whole, but there is no presumption that all should bear equal cuts. In fact, a key question for EU climate policy has been how to allocate reduction requirements across EU countries in order to achieve the overall EU target. The answer inevitably involves equity considerations.[1] An overall EU reduction target will only be approved by the parliaments of the EU member countries if the implied distribution of economic costs across EU regions is viewed as fair.

To what extent are policy proposals for reductions schemes consistent with equity considerations? We "translate" the burden sharing rules defined over two major abatement proposals, flat rate reduction targets and differential reduction targets based on the conclusions of the EU Council of Ministers (COM [1999], Annex 1), into welfare impacts.

One difficulty that must be recognized in any calculation of an equitable sharing of the burden of abatement is that the underlying economy will react to the proposed allocation of the burden. That is, if "equitable" carbon limits are varied across EU members then we would expect that there would be behavioral reactions, causing the assumptions under which the initial limits were determined to be equitable to become invalid. In short, the burden sharing rule needs to be endogenous to some model of the economy in order to derive an allocation of emission reductions across EU countries which is equitable by some welfare metric. The second step in our evaluation, then, is to ask if there exists an endogenous burden sharing rule which will indeed equalize the welfare impacts across member countries. We find that such rules do exist, but are sensitive to (i) the precise degree of aversion to inequity that applies to member states, (ii) the ability of EU members to trade emission rights openly amongst themselves, and (iii) to alternative baseline energy projections which determine the emission intensity of GDP in the business-as-usual reference case.

Our main findings have to do with the distributional impacts of alternative ways in which the EU could distribute an aggregate EU reduction target across its member

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[1] The EU Council of Ministers (Environment) has agreed that "the initial distribution between Member States will be reviewed by the Council ... in any case after completion of protocol negotiations ... taking account of the principles and approaches of ... equitable burden sharing among Member States with regard to the overall emission reduction objective by the Community as a whole ..." (European Commission [1997], paragraphs 17, 11-14).

states. In addition we investigate the potential for efficiency gains from trade with different allocations rules. The key insights from our analysis are as follows:

- Adopting the EU’s assumption on the baseline development of EU economies, neither differentiated targets based on the burden sharing proposal of the EU Council of Ministers nor a flat reduction produces an equitable outcome in welfare terms. When equity is an explicit concern, Germany, France, and the Netherlands will have to accept larger cuts in emission rights than the average, Denmark and the United Kingdom fall slightly below the average and Italy, and Spain will even be allowed to increase their emission over 1990 levels. Compared to the differentiated reduction targets proposed by the EU Council of Ministers, an equitable burden sharing implies that Germany, Denmark, Italy, and the United Kingdom are allocated more emission rights whereas France, Spain, and the Netherlands will obtain less emission rights. The derived pattern for an equitable permit allocation is determined by the “comparative advantage” across countries of mitigating carbon emissions given their benchmark economic structure.
- The welfare implications of different reduction schemes are correlated with exogenous projections of GDP growth rates and improvements in carbon efficiency. These projections determine the carbon emissions in the baseline, which serve as the reference point for emission cutbacks with respect to 1990 levels. As might be expected, the overall magnitude and cross-country differences in welfare costs of abatement are closely tied to differences in reduction requirements for countries with respect to their reference emission level in 2010. The importance of the baseline projections for an equitable burden sharing scheme highlights the need for a broad consensus on the future development of the different EU economies among climate policy negotiators of the member states.
- The overall efficiency gains from allowing trading of carbon emissions rights within the EU are limited. The reason is that cross-country differences in marginal abatement costs are relatively small and are quickly “absorbed” when limited low-cost abatement options are exhausted by polluters with high abatement cost.

We draw these conclusions from simulations of a large-scale computable general equilibrium (CGE) model of EU production, trade and energy usage. The model is originally due to Böhringer, Ferris and Rutherford [1998], and is extended to consider endogenous burden sharing. In Section 2 we provide a non-algebraic model description, in Section 3 we review the scenarios, in Section 4 the results are presented, and in Section 5 we provide some final remarks.

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2 Model Structure and Parameterization

2.1 Regional and Sectoral Disaggregation

We use a static 7-region, 17-sector CGE model[2] of the EU. The regional disaggregation covers seven EU member countries which account for the largest part of EU GDP, trade and carbon emissions: Denmark (DK), Spain (ES), France (FR), Germany (GE), Italy (IT), the Netherlands (NL) and the United Kingdom (UK). All other EU and non-EU regions are represented by an aggregate Rest of the World (ROW) whose representation is reduced to import and export flows to the EU countries.

At the sectoral level the model provides sufficient detail on sector-specific differences in factor intensities, degrees of factor substitutability and price elasticities of output demand in order to trace back the structural change in industrial production induced by a policy shift. With respect to the analysis of carbon abatement policies, the sectors in the model have been carefully selected to keep the most carbon-intensive sectors in the available data as separate as possible. The energy goods identified in the model include coal (COA), gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). This dis-aggregation is essential in order to distinguish energy goods by carbon intensity and the degree of substitutability. In addition the model features important carbon-intensive and energy-intensive industries which are potentially those most affected by carbon abatement policies. Specifically, the remaining sectors are: agriculture (AGR), iron and steel (ORE), chemical products (CHM), non-ferrous metals (NFM), non-metallic minerals (NMM), machinery (MAC), transport equipment (TEQ), paper pulp and printing (PLP), wood and wood products (WOO), food processing beverages and tobacco (FOO), textiles and leather (TEX), transport (TRN), and other industries (Y). Table 1 provides a summary of the sectors and regions included in the model.

2.2 Factor Markets

Primary factors include labor and capital, which are assumed to be mobile across sectors within each region but not internationally mobile. In fossil fuel production part of the capital is treated as a sector-specific resource, consistent with exogenous own-price elasticities of supply. Factor markets are assumed to be perfectly competitive such that flexible prices of factors ensures market clearance.

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[2] See Appendix A for an algebraic summary of the model.

2.3 Production

Nested, separable constant elasticity of substitution (CES) production functions are employed to specify substitution possibilities in domestic production between capital, labor, energy and material inputs. At the top level material inputs are used in fixed proportions, together with an aggregate of energy and a value added composite of labor and capital. The value added composite is a CES function of labor and capital. The energy aggregate is produced with a CES function of a primary energy composite and electricity. The primary energy composite is then a CES function of coal, crude oil, refined oil and natural gas. In fossil fuel production sector-specific resources are assumed in order to constrain supply responses to appropriate elasticities.

2.4 Final Demand

Final demand of the representative consumer in each region is given as a CES composite which combines consumption of an energy aggregate and a non-energy consumption bundle. The consumption composite is a CES function of the energy composite described above and an aggregate of non-energy goods. The latter consists of the 12 non-energy goods in the model, whose substitution possibilities are given by a CES function.

2.5 Public Expenditure and Investment Demand

Government demand within each region is fixed at exogenous real levels. Public goods and services are produced with a Cobb-Douglas aggregation of commodity inputs. Savings are determined through a constant marginal propensity to save by private households, and market clearance ensures a savings-investment equality. In each region investment is a Leontief aggregation of Armington inputs, which are composed of domestic and imported commodities.

2.6 International Trade

Trade between EU regions is specified using the Armington approach to product heterogeneity, so domestic and foreign goods of the same variety are distinguished by origin. The Armington composite for a traded good is a CES function of an imported composite and domestic production for that sector. The import composite is then a CES function of an EU import composite and a ROW import. The EU composite in turn is a CES function of production from all other EU countries.

EU countries are assumed to be price-takers with respect to world market prices, so that we have perfectly elastic ROW import-supply functions and ROW export-demand functions. There is an imposed balance of payment constraint to ensure trade balance between the EU and ROW. That is, the value of imports from the ROW to the EU must equal the value of exports from the EU to the ROW after including a constant benchmark trade surplus.

2.7 Welfare Cardinalization

In order to consider the equity implications of carbon taxes on different EU countries, we employ a "cardinalized" welfare index for each representative household. We do this in order to endogenously compute "fair" distributions of emission rights across EU countries.

Specifically, we employ a cardinalization of utility which is consistent with a constant coefficient of inequality aversion, a convenient formulation widely used in welfare economics.[3] The welfare impact on region r is assessed by changes in $W_r = U_r^{1-\rho} / (1-\rho)$, where U_r is a linearly homogeneous consumption welfare index defined over the infinite horizon. Values of ρ ranging from 0 up to ∞ provide simple representations of social welfare functions ranging from Utilitarian to Leontief-Rawlsian. We specify a range of values for ρ parametrically, and trace out how our policy conclusions change as we allow for more aversion to inequality across regions.

2.8 Model Calibration: Forward Projection to 2010

An important feature of any burden-sharing rule is the extent to which it binds the economies in the future. The economic consequences of emission abatement depend to a large extent on the structural characteristics of each particular economy exhibited in the reference situation.[4] With significant (exogenous) improvements in emission intensity until 2010, for example, the Kyoto abatement target will be less stringent for the European economy. Hence emission reduction from 2010 levels toward the Kyoto target, which refers to 1990 levels, will be less costly.

In our analysis we take the most recent consistent economic and energy flow data (see Appendix B) and undertake a forward projection of the European economy

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[3] Atkinson [1970], Boadway and Bruce [1984; p.277] and Layard and Walters [1978; p.48].

[4] The EU Council of Ministers (Environment) concludes that "... the equitable burden sharing among Member States ... will be discussed and agreed having regard.... to the aspects such as differences in starting points, economic structures and resource bases" (European Commission [1997], paragraph 12).

based on the assumptions of an official EU study, "Energy in Europe - European Energy to 2020" (European Commission [1996]). In other words, we use the official EU projections of key economic indicators (see Table 3) to infer the structure of the EU economy for 2010, which is the reference year for our abatement counterfactuals.[5] Table 3 shows that these projections indicate an overall increase of carbon emissions of 7% between 1990 and 2010 for the EU countries included in our model. They also entail considerable variation of emission efficiency improvements, and hence percentage emission increases, across member states.

One concern with these projections is the optimistic nature of the improvements in carbon intensity that are implied. Historical trends would suggest that improvements of as much as 1% over any sustained period would be very high indeed, so implied rates in excess of 2% are extreme.[6] We regard the problem of consistent projections of the future economies of the EU to be surprisingly under-studied.[7] For present purposes we accept the numbers provided by EU Conventional Wisdom projections.[8]

3 Scenario

The EU is committed to a reduction in greenhouse gas emissions for the EU as a whole and has held that position ever since the Rio de Janeiro conference in 1992. This target is currently set at an 8% reduction of 2010 emissions compared to 1990. The policy issue here is to evaluate alternative ways in which it could distribute this overall goal within the EU.[9] We do not consider the possibility that the EU may be able to undertake "joint implementation" strategies outside the EU that allow it to meet its aggregate target by paying other non-EU countries to actually effect reductions in emissions.[10]

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[5] See Böhringer, Jensen and Rutherford [2000; p.219] for a detailed description of the baseline calibration routine.

[6] A poll of 22 experts reported in Manne and Richels [1994] results in an average autonomous energy efficiency improvement value of 0.7%.

[7] Böhringer, Jensen and Rutherford [1998] provide an analysis of the implications of alternative baseline energy projections on the costs of carbon abatement in the EU.

[8] See European Commission [1996; p.142-143] for a general description of the assumptions for the Conventional Wisdom Scenario underlying our model calibration.

[9] We restrict our analysis to the abatement of carbon dioxide. CO_2 emissions are the major source of the anthropogenic greenhouse effect.

[10] The possibility of joint implementation with non-EU countries might significantly change the total cost of EU abatement as well as the distributional impacts across EU member countries. Harrison and Rutherford [1998] address this issue from the perspective of global burden-sharing.

For our welfare evaluation of alternative burden-sharing rules we hold the aggregate EU cutback constant and assume that leakage[11] outside the EU is relatively unaffected by the method by which the EU achieves its reduction target. The gross benefit of abatement for a given (representative) household in each region is then constant over all burden sharing scenarios, and we can just concentrate on the "price tag" for the EU of delivering a public good called "aggregate EU abatement".

3.1 Burden Sharing Rules

We evaluate three alternative ways of allocating emission rights across coalition members.

3.1.1 DIFF: Differential Percentage Cuts

One exogenous allocation rule, called DIFF, refers to differentiated national reductions in 2010 where emission rights are distributed among EU countries according to the burden-sharing proposal of the EU Council of Ministers (COM [1999], Annex 1). For the countries incorporated in our model these reduction[12] targets are: Denmark 21%, Germany 21%, Spain -15%, France 0%, Italy 6.5%, the Netherlands 6%, and the United Kingdom 10%. For our analysis we scale the reduction targets uniformly across countries such that the aggregate reduction of these countries together amounts to 8%. This yields the following differential cutbacks in emission rights as compared to 1990 emission levels: Denmark 16.6%, Germany 16.6%, Spain -11.8%, France 0%, Italy 5.1%, the Netherlands 4.7%, and the United Kingdom 7.9%.

3.1.2 UNIF: Uniform Proportional Cuts

An alternative exogenous allocation rule, called UNIF, uses uniform proportional cuts of 8% in all EU regions which reflects proposals for a flat rate emission reduction as stated by several parties of the Framework Convention on Climate

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[11] It is possible to make some attempt to estimate the effects of leakage in a small, open economy (Harrison and Kriström [1998]), and this idea could be applied here as well to the ROW. The idea is to assume that all net trade effects generated by some policy in the country generate emissions according to some assumed foreign emissions coefficient. The problem with this calculation in the present case is that our ROW is an amalgam of many diverse countries, and the carbon coefficients could vary enormously depending on which countries actually undertake that trade. For example, if China undertakes the trade there would be much more leakage than if Japan undertakes it. We prefer to remain explicitly agnostic on the leakage issue, leaving that to global models to account for (e.g. Harrison and Rutherford [1998]).

[12] Negative percentages refer to allowed increases in emissions.

Change (United Nations [1995]). This is clearly equitable in terms of the metric of the percentage cut in abatement, but need not be equitable with respect to welfare. With this allocation rule the emissions allocations for EU members are formulated as fixed shares of EU aggregate emissions.

3.1.3 ENDOG: Endogenous Targets to Equalize Welfare Changes

The third allocation rule is endogenous, and is imaginatively called ENDOG. It shares the burden of carbon abatement differentially across EU member countries so as to equalize the welfare impact across EU members. We cardinalize utility to approximate in formal terms what might be meant by "fair", and we then let the model allocate emission rights within the EU to produce an equal welfare burden across regions. Specifically, we impose the constraint that:

$$\frac{W_r^{1-\rho}}{1-\rho} - \frac{\overline{W}_r^{1-\rho}}{1-\rho} = \Delta W^{EU}$$

where $\overline{W}_r$ is the base year level of the welfare index for region r and the parameter ρ reflects the degree of aversion to inequalities in welfare impacts across EU member states.[13] This rule constrains the burden to be shared so that it is the same for each EU country in terms of the cardinalized change in welfare.

3.2 Tradable Permits

In any of the scenarios permit prices can be interpreted as carbon tax rates which are necessary to produce an abatement outcome equivalent to the total amount of emission permits in use. Revenues from carbon permits accrue to the representative consumer in each region.[14] We evaluate two regimes with respect to the use of carbon emission permits in the EU.

3.2.1 NO_TRD: No Trade in Emission Permits Across National Borders

In this case, called NO_TRD, permit rights cannot be traded across the borders of EU member countries. The price of emission rights will typically differ across regions. In the event that a country's emissions fall below the constraint it must meet, there is no carbon tax imposed.[15]

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[13] As ρ increases, the aversion to inequality of welfare impacts increases also.

[14] The shadow price of emission permits is then zero, reflecting the fact that emission rights are not scarce.

[15] We do not analyze the public finance issue of how existing tax distortions, and the method of revenue recycling, affect the welfare implications of carbon abatement (see Goulder [1995] for an overview).

3.2.2 TRD: Trade in Emission Permits Across National Borders

In this regime, denoted TRD, we allow tradable permits throughout EU regions. Trade will ensure that the prices of permit rights are equalized across all EU countries, hence marginal abatement costs will also be equalized.

4 Results

4.1 Basic Results

Table 4 presents the main results from our core scenarios. Block A shows the welfare cost in terms of percentage changes in (Hicksian) equivalent variation in real income. The aggregate welfare impacts are the composition of substitution effects (domestic and international) as well as cross-country income effects triggered by the imposition of carbon emission constraints. It is worth emphasizing that our welfare measure does not show any effects from the reduction in global carbon emissions that these policies generate. We implicitly assume that these gross benefits are separable from the welfare derived from consumption of private goods, and focus on the latter.[16] Block B shows marginal abatement costs expressed in terms of 1995 US dollars per ton of carbon abated. These costs are equivalent to the price of emission permits, or carbon tax rates which have to be levied in order to meet the exogenous reduction target. Block C reports the percentage reduction in emissions in each region and in the EU compared to 1990 levels. Block D lists the emission cutbacks for each country as compared to projected 2010 benchmark emission levels.

4.1.1 Equalizing Welfare Impacts Implies "Different Differential" Targets

In the no-trade regime the welfare cost to each EU state is equalized at 0.36% of equivalent variation in income when we allow endogenous burden-sharing (ENDOG/NO_TRD). Block C shows that an equitable burden sharing rule implies a non-uniform, differential emission right allocation, but that distribution of emission rights is quite unlike the exogenous profile DIFF. As compared to reduction targets based on the burden sharing proposal by the EU Council of Ministers, Denmark, Germany, Italy, and the United Kingdom should be endowed

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[16] Alternative approaches are either to specify some explicit damage function or to constrain the model to keep aggregate emission reductions constant over all scenarios. The former approach has been popular in several recent studies, despite the acknowledged lack of any hard data on the specification of the damage function.

with more emission rights whereas France, Spain, and the Netherlands should face a cut in emission rights.

To understand the nature of infra-marginal abatement costs consider the cutback in emission rights effected by the alternative allocation schemes compared to the 2010 baseline.

From Table 4D we see that equitable cutbacks of emissions across countries range from 12% (Italy) up to 21% (the Netherlands). The endogenous reduction scheme reflects differences in the benchmark economic structure across EU countries, such as variations in the carbon efficiency of the energy system, differences in the fuel mix, and trade relations with other countries which determine the aggregate welfare costs of emission abatement for any individual country. For an equitable outcome the extent of abatement has to outweigh cross-country differences in the ease of carbon substitution through fuel switching or energy savings[17], as well as the country-specific opportunities for tax-burden shifting through changes in the terms of trade.

The marginal abatement costs under ENDOG depend to a large extent on differences in the carbon intensity of different sectors across countries. For example, France faces much higher marginal abatement costs compared to Denmark to achieve an almost identical relative cutback of carbon emissions. The reason is that France is not carbon-intensive in sectors with low-cost substitution possibilities, such as electricity generation, and carbon-intensive in sectors where carbon substitution is relatively costly (e.g., final demand). Therefore, the carbon tax rates needed to produce the same relative carbon abatement are higher in France than in Denmark, which has low cost substitution possibilities in carbon-intensive sectors (e.g., power generation).

The range of marginal abatement costs under ENDOG/NO_TRD is much more narrow than those associated with DIFF/NO_TRD or UNIF_NO_TRD. The larger variation of carbon tax rates under DIFF/NO_TRD and UNIF/NO_TRD can be attributed directly to the larger differences in the required extent of abatement across countries. With DIFF/NO_TRD, Denmark, Germany, Italy, and the United Kingdom suffer the highest welfare losses because these countries have to achieve large carbon cutbacks, requiring high carbon taxes with severe distortionary effects on domestic production and consumption. When equity is considered, the first order of business is to assign reduced emission targets (more emission rights) to Denmark, Germany, Italy, and the United Kingdom to help them mitigate their relatively worse welfare position: this is the explicit goal of the constrained optimization underlying our ENDOG calculations. Since Denmark, Germany, Italy, and the United Kingdom are reducing their abatement level, somebody else

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[17] For a single country carbon abatement gets increasingly more expensive with higher reduction targets when low-cost options, such as cheap fuel-switching in electricity production from coal to gas, have been exhausted.

in the EU must be increasing their abatement level in order to maintain the same aggregate EU reduction. Equalization of welfare cost across countries then implies that France, Spain, and the Netherlands have to undertake higher emission reductions.

4.1.2 Trade in Carbon Rights Improves Welfare, But Gains From Trade Are Rather Limited

EU-wide cost effectiveness of carbon abatement suggests that marginal costs of emission reduction should be equalized across sources. With respect to EU welfare, a tradable permit system which leads to uniform permit prices (or uniform carbon taxes) should be Pareto-superior to the NO_TRD cases where differences in the marginal costs of abatement are not exploited. The welfare figures in Block A confirm this economic intuition, but also indicate that the scope for efficiency gains from coordinated action is rather limited. As expected, the magnitude of the efficiency gains is positively correlated with differences in marginal abatement costs across countries. For UNIF/NO_TRD, where the relative variations in marginal abatement costs is most distinct, a shift to tradable permits produces efficiency gains of around 10% of EU-wide abatement costs. Under DIFF/NO_TRD and, ENDOG/NO_TRD, the variation of abatement costs is much smaller and so are the efficiency gains from permit trade.

The pattern of permit trade for alternative allocation rules can be explained on the basis of marginal abatement costs for the NO_TRD scenarios. Countries whose marginal abatement costs under NO_TRD are below the uniform permit price under TRD will sell permits and abate more. In turn, countries whose marginal abatement costs under NO_TRD are above the uniform permit permit price under TRD will buy permits and abate less. Trade in permits does not benefit all countries. The sign of the welfare change for an individual region depends on the relative strength of the associated domestic substitution effect and the terms of trade effects (i.e., international substitution effect plus income effect).[18] With respect to permit trade, the welfare effects from the domestic substitution effect are opposite to the welfare effect from the terms of trade effect, with alternating signs for the permit sellers and permit buyers. Permit sellers face higher marginal abatement costs after trade. This worsens their welfare losses due to the domestic substitution effect, but on the other hand it improves their terms of trade. The opposite applies to countries which are purchasing permit rights. Only under ENDOG_TRD will all countries benefit from emission trading since efficiency gains are, by definition, equally distributed across trading partners.

Finally, comparing entries for EU under UNIF/TRD and ENDOG/TRD in Table 4A, we find a trade-off between equity and efficiency in carbon abatement for the

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[18] Income effects also include tax shifting and transfers through permit sales or purchases.

EU economy. A flat rate emission reduction produces different income effects, which in turn can affect the overall efficiency losses for the EU from carbon abatement due to associated changes in relative prices.

4.2 Equity Concerns

How do the results change when we vary the extent to which equity effects matter? We can analyze this question by parametrically varying the cardinalization of welfare changes in the model. The results are reported in Table 5.

Comparing the NO_TRD cases, we see that reducing the aversion to inequality of welfare impacts implies that Spain bears a larger share of the aggregate EU cutback. Spain’s emission cutback as compared to 2010 baseline levels increases from 16.4% (ENDOG1) to 20.8% (ENDOG0). Conversely, if we have more of an aversion to inequality Spain has a significantly smaller cutback imposed: only 12.5% under ENDOG2. Italy is affected by varying degrees of aversion to inequality the same way as Spain, although the effect is much less pronounced.

Since Spain and Italy are bearing more of the burden under reduced inequality aversion, who is getting off with less? Denmark gains with less concern about inequality, as does Germany. France, the Netherlands and the United Kingdom are relatively unaffected by these varying degrees of equity angst. So concerns about equity translate here into de facto transfers from Danish and German households to Spanish and Italian households. These transfers are being effected through a distortionary scheme, the distribution of emissions targets, rather than in some lumpsum form. Although it is customary and appropriate to question the real world efficacy of lumpsum transfers, the EU has necessarily[19] developed these to a fine art through creative accounting for regional disparities.

The welfare implications of varying degrees of aversion to inequality are directly related to changes in the allocation of emission rights. Whereas Denmark and Germany suffer higher welfare losses with more concern about inequality, Spain and Italy gain.

4.3 Sensitivity Analysis to Baseline Projections

The magnitude and the distribution of abatement costs for meeting the Kyoto target through alternative permit allocation rules across EU countries depends on

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[19] Due to the use of unanimity voting in many issues of EU policy. Unanimity can be more efficient than majority rule when there exists some “costless” means of making sidepayments from voter to voter. One can view the development of sidepayment mechanisms in the EU as one rational public choice response to the constraint of having to use unanimity.

the evolution of anthropogenic carbon emissions in the baseline (Business as Usual). The baseline emission level determines the extent to which emission control commitments with respect to 1990 emission levels actually constrain the economies. Carbon emissions are directly linked to the combustion of fossil fuels, so it follows that baseline assumptions about GDP growth rates, energy efficiency improvements, and the future fuel mix, matter for the reference level of carbon emissions. For our baseline projection we have used official EU data. In our sensitivity analysis we analyze the changes in welfare associated with alternative burden sharing rules keeping the evolution of EU countries rather uniform. For this purpose we take the EU average across country-specific values of key indicators (listed in Table 3) and use these average values for model calibration.

The effects of making these projections to 2010 are displayed in Table 6. By comparing these results to the effects using our original baseline (in Table 4), we see how crucial the choice of the baseline is.[20] An alternative projection of the future EU economy which abstracts from cross-country differences in growth rates substantially changes the country-specific welfare implications of the DIFF and UNIF permit allocations.

To interpret the results at the country level we have to keep in mind that the magnitude of welfare costs depends on the effective reduction requirement determined by the individual reduction target with respect to 1990 levels and the baseline emission level in 2010. The latter depends on GDP growth rates and projected improvements in CO_2 intensity. Under DIFF Denmark experiences the most severe welfare loss because a high reduction target goes together with high baseline emissions, yielding an effective reduction target of almost 35%. Table 3 indicates the reasons for the higher baseline emissions. Under uniform projections Denmark has a higher GDP growth rate and a considerably smaller improvement in CO_2 intensity as compared to the differential projections used in our core scenarios. The same reasoning applies for the United Kingdom though the increase in reduction requirement and welfare costs relative to the original baseline is much less pronounced. For France, the Netherlands and Germany the reduction requirements (as well as the implied welfare costs) remain relatively constant because the uniform projections on GDP growth and carbon intensity improvements are relatively consistent with the initial country-specific values. Spain and Italy find it easier to meet their domestic policy targets with respect to

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[20] Calibration of the model along the time path involves a two-step approximation of autonomous energy efficiency improvement factors, which scale energy demand functions to match exogenous emissions as close as possible taking into account given potential GDP growth rates, changes in the fuel mix of electricity generation, and world market prices (see Böhringer, Jensen, Rutherford [2000; p.219]). Calibrating the model to EU average values as well as to our baseline values, we set the same emission target in both case but cannot assure that both calibrations yield the same approximated overall EU emission level. This explains the difference in the overall EU emission level between the baseline and our sensitivity analysis.

1990 emission levels because smaller GDP growth rates and higher improvements in carbon intensity yield a lower reference emission level.

For a flat rate, uniform cutback of emission rights based on 1990 levels the variation of effective abatement requirements across countries, and hence the differences in welfare costs, become less pronounced. Nevertheless, the UNIF (NO_TRD) allocation scheme is still far from producing an equitable outcome.

Adjustments in the endogenous allocation of emission rights under ENDOG/NO_TRD reflect how the revised benchmark economic structure change the "comparative advantage" across countries of mitigating carbon emissions.

5 Concluding Remarks

We evaluated the welfare implications of alternative ways in which the EU could distribute an aggregate EU reduction target across its member states. We compared a uniform proportional cutback in emissions and the actual EU burden sharing agreement with an equitable allocation scheme derived from an endogenous burden sharing calculation in which the welfare cost across member states is equalized.

Our current modeling framework ignores several issues which are potentially important for the analysis of burden sharing. Lines of future research include:

- the incorporation of national energy policy constraints, such as a nuclear phase-out;
- a more detailed projection of the future economic development, in particular projections of (non price-induced) energy efficiency improvements;
- the inclusion of the other EU countries to assess the potential efficiency gains from trade in permits; and
- the inclusion of other non-EU countries that are differentiated with respect to carbon intensities to allow a more complete evaluation of "carbon leakage" and "joint implementation".

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Table 1: Sectors and Regions in the Model.

Production Sectors (in brackets labels of Eurostat's R59 standard)		Regions	
Energy		1. DE	Germany
1. COA	Coal (031, 033)	2. DK	Denmark
2. CRU	Crude oil (071)	3. ES	Spain
3. OIL	Refined oil (073)	4. FR	France
4. GAS	Natural and manufactured gases (075, 098)	5. IT	Italy
5. ELE	Electricity and steam (097, 099)	6. NL	Netherlands
		7. UK	United Kingdom
Non-Energy			
6. AGR	Agriculture (010)		
7. ORE	Iron and steel (135, 136)		
8. CHM	Chemical products (170)		
9. NFM	Non-ferrous metals (137)		
10.NMM	Non-metallic minerals (151, 153, 155, 157)		
11. MAC	Machinery (190, 210, 230, 250)		
12. TEQ	Transport equipment (270, 290)		
13. PLP	Paper pulp and printing (471, 473)		
14. WOO	Wood and wood products (450)		
15. FOO	Food processing beverages and tobacco (310, 330, 350, 370, 390)		
16. TEX	Textiles and leather (410, 430)		
17. TRN	Transport (611, 613, 617, 631, 633, 650)		
18. ROI	Other industries (095, 490, 510, 530, 550, 570, 590, 670, 690, 710, 730, 750, 770, 790, 810, 850, 890, 930)		

Table 2: Key Elasticities Assumed in the Model.

Exports EU Region/Exports EU Region	4
Imports/Domestic Production	4
Labor-Capital/Energy	0.3
Labor/Capital	1.0
Electricity/Fuels	0.8-1.2
Fuel/Fuel	0.8

Table 3: Baseline Assumptions for 1995-2010 (EU 1996).

	DE	DK	ES	FR	IT	NL	UK	EU
A. Average GDP growth rates (in % per annum)								
	2.7	2.3	2.7	2.6	2.2	2.3	2.3	2.5
B. Average CO2 growth rate (in %)								
	0.5	-0.3	1.0	0.5	1.1	0.4	0.3	0.6
C. Average growth rates for fossil fuel inputs to power generation (in % per annum)								
COA	-0.6	-1.8	-0.5	-7.2	1.3	-2.5	-5.5	-1.8
GAS	5.2	9.1	9.5	9.1	6.3	3.3	8.5	6.5
OIL	1.1	-1.2	0.2	-15.2	-4.0	-5.1	-0.3	-2.2
D. Implied average improvement in CO2 intensity (in % per annum)								
	2.1	2.6	1.7	2.0	1.1	1.9	2.0	1.9
E. Total carbon emission (in million tons of CO2)								
1990	976.3	52.0	206.5	366.7	403.6	156.5	579.8	2741.3
1995	894.9	61.4	216.2	362.7	395.1	159.7	583.0	2672.8
2010	969.8	58.3	251.7	391.9	462.4	170.0	608.0	2912.0

Table 4: Effect of Burden Sharing Rules & Tradable Emissions Permits in Base Years (2010).

	DIFF		UNIF		ENDOG	
	NO_TRD	TRD	NO_TRD	TRD	NO_TRD	TRD
A. Welfare Change as Percent of Income						
DE	-0.51	-0.51	-0.20	-0.26	-0.36	-0.35
DK	-0.71	-0.61	-0.39	-0.44	-0.36	-0.35
FR	-0.11	-0.13	-0.27	-0.25	-0.36	-0.35
ES	-0.11	-0.11	-0.86	-0.54	-0.36	-0.35
IT	-0.59	-0.47	-0.71	-0.52	-0.36	-0.35
NL	-0.12	-0.08	-0.15	-0.17	-0.36	-0.35
UK	-0.41	-0.41	-0.42	-0.41	-0.36	-0.35
EU	-0.37	-0.35	-0.41	-0.36	-0.36	-0.35
B. Carbon Taxes in 1995 USD per Ton						
DE	70	66	31	66	50	66
DK	90	66	55	66	51	66
FR	35	66	86	66	107	66
ES	40	66	168	66	91	66
IT	111	66	132	66	68	66
NL	42	66	54	66	86	66
UK	70	66	71	66	60	66
EU	66	66	66	66	66	66
C. Percentage Emission Cut as Compared to 1990 Levels						
DE	16.6	15.8	8.0	15.8	12.6	15.8
DK	16.6	10.8	8.0	10.8	6.8	10.8
FR	0	5.3	8.0	5.3	10.7	5.3
ES	-11.8	-6.5	8.0	-6.6	-2.2	-6.6
IT	5.1	-1.5	8.0	-1.5	-1.1	-1.5
NL	4.7	10.6	8.0	10.7	14.9	10.7
UK	7.9	7.3	8.0	7.3	6.4	7.3
EU	8.0	8.0	8.0	8.0	8.0	8.0
D. Percentage Emission Cut as Compared to 2010 Levels						
DE	16.1	15.3	7.4	15.3	12.1	15.3
DK	25.6	20.4	17.9	20.4	16.9	20.4
FR	6.5	11.4	13.9	11.4	16.4	11.4
ES	8.4	12.8	24.7	12.7	16.4	12.8
IT	17.2	11.4	19.7	11.4	11.7	11.3
NL	11.5	17.0	14.5	17.0	21.0	17.0
UK	12.2	11.6	12.3	11.6	10.8	11.6
EU	13.4	13.4	13.4	13.4	13.4	13.4

Table 5: Effects of Varying Degrees of Aversion to Inequality of Welfare Impact.

	ENDOG0		ENDOG1		ENDOG2	
	NO_TRD	TRD	NO_TRD	TRD	NO_TRD	TRD
A. Welfare Change as Percent of Income						
DE	-0.31	-0.30	-0.36	-0.35	-0.42	-0.40
DK	-0.26	-0.25	-0.36	-0.35	-0.51	-0.49
FR	-0.34	-0.32	-0.36	-0.35	-0.39	-0.38
ES	-0.60	-0.57	-0.36	-0.35	-0.22	-0.21
IT	-0.40	-0.38	-0.36	-0.35	-0.33	-0.32
NL	-0.37	-0.36	-0.36	-0.35	-0.35	-0.34
UK	-0.37	-0.36	-0.36	-0.35	-0.35	-0.34
EU	-0.37	-0.36	-0.36	-0.35	-0.36	-0.35
B. Carbon Taxes in 1995 USD per Ton						
DE	44	66	50	66	56	66
DK	37	66	51	66	69	66
FR	100	66	107	66	113	66
ES	129	66	91	66	65	66
IT	76	66	68	66	61	66
NL	87	66	86	66	84	66
UK	62	66	60	66	58	66
EU	66	66	66	66	66	66
C. Percentage Emission Cut as Compared to 1990 Levels						
DE	11.3	15.8	12.6	15.8	13.9	15.8
DK	2.6	10.7	6.8	10.8	11.5	10.8
FR	9.9	5.3	10.7	5.3	11.3	5.3
ES	3.3	-6.6	-2.2	-6.6	-6.8	-6.5
IT	0.1	-1.5	-1.1	-1.5	-2.4	-1.5
NL	15.3	10.7	14.9	10.7	14.5	10.7
UK	6.7	7.3	6.4	7.3	6.1	7.3
EU	8.0	8.0	8.0	8.0	8.0	8.0
D. Percentage Emission Cut as Compared to 2010 Levels						
DE	10.8	15.3	12.1	15.3	13.4	15.3
DK	13.1	20.4	16.9	20.4	21.1	20.4
FR	15.7	11.4	16.4	11.4	17.1	11.4
ES	20.8	12.7	16.4	12.8	12.5	12.8
IT	12.8	11.4	11.7	11.3	10.6	11.3
NL	21.3	17.0	21.0	17.0	20.6	17.0
UK	11.1	11.6	10.8	11.6	10.5	11.6
EU	13.4	13.4	13.4	13.4	13.4	13.4

Table 6: Sensitivity Analysis with Respect to the Baseline Assumptions.

	DIFF		UNIF		ENDOG	
	NO_TRD	TRD	NO_TRD	TRD	NO_TRD	TRD
A. Welfare Change as Percent of Income						
DE	-0.61	-0.58	-0.25	-0.31	-0.38	-0.37
DK	-1.83	-1.04	-1.23	-0.86	-0.38	-0.37
FR	-0.13	-0.15	-0.3	-0.27	-0.38	-0.37
ES	-0.02	0.05	-0.51	-0.39	-0.38	-0.37
IT	-0.35	-0.34	-0.44	-0.40	-0.38	-0.37
NL	-0.17	-0.11	-0.20	-0.21	-0.38	-0.37
UK	-0.60	-0.52	-0.60	-0.52	-0.38	-0.37
EU	-0.41	-0.37	-0.40	-0.37	-0.38	-0.37
B. Carbon Taxes in 1995 USD per Ton						
DE	77	67	35	67	50	67
DK	183	67	133	67	48	67
FR	39	67	89	67	107	67
ES	12	67	122	67	99	67
IT	72	67	93	67	78	67
NL	44	67	54	67	81	67
UK	91	67	91	67	61	67
EU	67	67	67	67	67	67
C. Percentage Emission Cut as Compared to 1990 Levels						
DE	16.6	14.8	8.0	14.8	11.4	14.8
DK	16.6	-6.4	8.0	-6.5	-11.9	-6.7
FR	0.0	4.9	8.0	4.9	10.3	4.9
ES	-11.8	0.1	8.0	0.0	4.9	0.0
IT	5.1	4.3	8.0	4.4	5.9	4.4
NL	4.7	11.2	8.0	11.3	14.4	11.3
UK	7.9	4.3	8.0	4.3	3.1	4.2
EU	8.0	8.0	8.0	8.0	8.0	8.0
D. Percentage Emission Cut as Compared to 2010 Levels						
DE	16.9	15.1	8.30	15.1	11.8	15.1
DK	35.4	17.6	28.8	17.6	13.4	17.4
FR	7.60	12.1	15.0	12.1	17.1	12.1
ES	2.40	12.8	19.7	12.7	17.0	12.8
IT	11.4	10.6	14.1	10.7	12.1	10.6
NL	13.3	19.2	16.2	19.2	22.1	19.2
UK	16.3	13.0	16.4	13.0	11.9	13.0
EU	13.7	13.7	13.7	13.7	13.7	13.7

Appendix A: Algebraic Model Summary of the Generic EU Model

Table 7: Summary of Prices and Output Quantities Determining an Equilibrium.

Summary of Prices	
P_{ir}	Output price of good i produced in region r
P_{ir}^{M}	Import price aggregate for good i imported to region r
P_{ir}^{E}	Composite price for aggregate energy inputs into sector i in region r (i=C for final consumption)
P_{r}^{C}	Composite price for aggregate household demand in region r.
P_{r}^{G}	Composite price for government demand in region r.
P_{r}^{I}	Composite price for investment demand in region r.
w_{r}	Economy-wide wage rate in region r
r_{r}	Rate of return for sector-specific capital inputs, sector j in region r
PCO	Price of carbon emission rights (carbon tax)
Summary of Quantity Indices	
Y_{jr}	Level of production, sector j in region r
C_{r}	Aggregate household consumption, region r
I_{r}	Aggregate investment, region r
G_{r}	Aggregate public output, region r

Table 8: Key Benchmark Shares, Endowment Parameters and Elasticities.

Key Benchmark Shares, Endowment Parameters and Elasticities	
θ_{ijr}^{M}	Import value share for sector i inputs to sector j in region r (j=G: government; j=C: household; j=I: investment)
α_{jr}^{E}	Energy input value share of KLE, sector j in region r
β_{jr}^{K}	Value shares for capital in value-added of sector j in region r
a_{jr}^{KLE}	Benchmark value share of capital, labor and energy inputs in sector j of region r
a_{ijr}	Benchmark value share of non-energy input i in sector j of region r
$\theta_{irr'}^{MM}$	Benchmark value share of region r exports in aggregate imports of good i into region r'
ε_{ijr}	Carbon emission coefficient for energy input i into sector j in region r
θ_{ijr}^{E}	Benchmark value share of energy good i in aggregate energy demand by sector j in region r (j=C: household)
$\overline{L_r}$	Aggregate labor endowment for region r
$\overline{K_r}$	Aggregate endowment of capital, region r
$CRTS_r$	Carbon emission rights endowment, region r
$\overline{G_r}$	Exogenously-specified demand for public output, region r
σ_{MM}	Elasticity of substitution between imports from different foreign countries
σ_{DM}	Elasticity of substitution between domestic and imported inputs or demands
σ_{E}	Elasticity of substitution between energy inputs

Exhaustion of Product Conditions

1. Production:

$$\pi_{jr}^{Y} \quad = \quad P_{jr} - \sum_{i \notin EG} a_{ijr} \left(\theta_{ijr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + \left(1-\theta_{ijr}^{M}\right) P_{ir}^{1-\sigma_{DM}} \right)^{\frac{1}{1-\sigma_{DM}}}$$

$$-a_{jr}^{KLE} \left[\alpha_{jr}^{E} {P_{jr}^{E}}^{1-\sigma_{DM}} + \left(1-\alpha_{jr}^{E}\right) \left(w_{r}^{(1-ß_{jr}^{K})} r_{r}^{ß_{jr}^{K}} \right)^{1-\sigma_{KLE}} \right]^{\frac{1}{1-\sigma_{KLE}}} = 0$$

2. Sector-specific energy demand:

$$\pi_{jr}^{E} \quad = \quad P_{jr}^{E} - \left[\sum_{i \in EG} \theta_{ijr}^{E} \left\{ \left(\theta_{ijr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + (1-\theta_{ijr}^{M}) P_{ir}^{\,1\text{-}\sigma_{DM}} \right)^{\frac{1}{1\text{-}\sigma_{DM}}} + \varepsilon_{ijr} PCO \right\}^{1-\sigma_{E}} \right]^{\frac{1}{1-\sigma_{E}}} = 0$$

3. Import demand:

$$\pi_{jr}^{M} \quad = \quad P_{jr}^{M} - \left(\sum_{r' \neq r} \theta_{jrr'}^{MM} P_{jr'}^{\;1-\sigma_{MM}} + \theta_{jROWr}^{MM} {P_{jROW}^{M}}^{\;1-\sigma_{MM}} \right)^{\frac{1}{1-\sigma_{MM}}} \quad = \quad 0$$

4. Investment:

$$\pi_{r}^{I} \quad = \quad P_{r}^{I} - \sum_{i} a_{ir}^{I} \left(\theta_{iIr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + \left(1-\theta_{iIr}\right) P_{ir}^{\;1-\sigma_{DM}} \right)^{\frac{1}{1-\sigma_{DM}}} \quad = \quad 0$$

5. Public output:

$$\pi_{r}^{G} \quad = \quad P_{r}^{G} - \prod_{i} \left(\theta_{iGr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + \left(1-\theta_{iGr}^{M}\right) P_{ir}^{\;1-\sigma_{DM}} \right)^{\frac{a_{ir}^{G}}{1-\sigma_{DM}}} \quad = \quad 0$$

6. Household consumption demand:

$$\pi_{r}^{C} \quad = \quad P_{r}^{C} - \left[\theta_{Cr}^{E} {P_{Cr}^{E}}^{1-\sigma_{EC}} + \left(1-\theta_{Cr}^{E}\right) \left\{ \prod_{i \notin EG} \left(\theta_{iCr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + \left(1-\theta_{iCr}^{M}\right) P_{ir}^{\;1-\sigma_{DM}} \right)^{\frac{\alpha_{ir}}{1-\sigma_{DM}}} \right\} \right]^{\frac{1}{1-\sigma_{DM}}} = 0$$

7. Household energy demand:

$$\pi_{Cr}^{E} \quad = \quad P_{Cr}^{E} - \left[\sum_{i \varepsilon EG} \theta_{iCr}^{E} \left\{ \left(\theta_{iCr}^{M} {P_{ir}^{M}}^{1-\sigma_{DM}} + \left(1-\theta_{iCr}^{M}\right) P_{ir}^{\;1-\sigma_{DM}} \right)^{\frac{1}{1-\sigma_{M}}} + \varepsilon_{iCr} PCO \right\}^{1-\sigma_{E}} \right]^{\frac{1}{1-\sigma_{E}}} = \; 0$$

Market Clearance Conditions

8. Labor:

$$\overline{L_r} = \sum_j Y_{jr} \frac{\partial \pi_{jr}^Y}{\partial w_r}$$

9. Capital:

$$\sum_r \overline{K}_r = \sum_{j,r} Y_{jr} \frac{\partial \pi_{jr}^Y}{\partial r_r}$$

11. Output:

$$\begin{aligned} Y_{ir} &= \sum_j Y_{jr} \frac{\partial \pi_{jr}^Y}{\partial P_{ir}} + C_r \frac{\partial \pi_r^C}{\partial P_{ir}} + I_r \frac{\partial \pi_r^I}{\partial P_{ir}} \\ &\quad + G_r \frac{\partial \pi_r^G}{\partial P_{ir}} + \sum_{r'} M_{i'r} \frac{\partial \pi_{i'r}^M}{\partial P_{ir}} + M_{irROW} \end{aligned}$$

12. Imports:

$$M_{ir} = \sum_j Y_{jr} \frac{\partial \pi_{jr}^Y}{\partial P_{ir}^M} + C_r \frac{\partial \pi_r^C}{\partial P_{ir}^M} + I_r \frac{\partial \pi_r^I}{\partial P_{ir}^M} + G_r \frac{\partial \pi_r^G}{\partial P_{ir}^M}$$

13. Balance of Payments:

$$\sum_{i,r} \overline{P_i^x} M_{irROW} = \sum_{i,r} \overline{P_i^M} M_{iROWr} + \sum_r \overline{B_r}$$

14. Final consumption demand:

$$C_r = \frac{\left(1 - mps_r\right)\left(w_r \overline{L_r} + r_r \overline{K_r} + PCO \cdot CRTS_r - P_r^G \overline{G_r} - \overline{B_r}\right)}{P_r^C}$$

15. Savings:

$$I_r = \frac{mps_r \left(w_r \overline{L_r} + r_r \overline{K_r} + PCO \cdot CRTS_r - P_r^G \overline{G_r} - \overline{B_r}\right)}{P_r^I}$$

16. Carbon emission permits:

$$\sum_{r} CRTS_{r} \quad = \quad \sum_{j,r} Y_{jr} \frac{\partial \pi^{Y}_{jr}}{\partial PCO}$$

Appendix B: Benchmark Data Sources and Reconciliation

The model is based on economic transactions in a particular benchmark year (2010 in our case). Benchmark data are used to calibrate parameters of the functional forms from a given set of benchmark quantities, prices and elasticities. Data for this model calibration stem from four different sources which need to be reconciled to yield a consistent benchmark data set.

First is the EUROSTAT [1995] input-output tables. The input-output data base covers the outputs and intermediate inputs of the 17 sectors of the model, the primary inputs (labor, profits, depreciation and production taxes), imports, and the final demand categories (consumption, investment, government expenditures and exports).

Second is the CHELEM trade data due to WEFA [1995]. The share parameters in the CES function for Armington imports across different regions are calculated using a trade matrix with bilateral trade flows.

Third is the IEA [1992] energy balances and energy prices/taxes. IEA statistics on physical energy flows and energy prices for industrial and household demands are used for the “bottom-up” calibration of energy demands and supplies as well as for the derivation of sector-specific and energy-specific CO_2 coefficients in CO_2 units per national currency units.

Fourth is the European Commission’s [1996] projection on the future development of the European economy.

Reconciliation of Eurostat input-output data and trade data is an important step in constructing the base year equilibrium. For this purpose, we employ a nonlinear least squares procedure to calibrate bilateral trade flows provided by CHELEM to the intra-EU and extra-EU trade totals provided in the Eurostat input-output tables (see Böhringer, Ferris and Rutherford [1998] for further discussion). CHELEM does not cover all trade flows, and for the missing goods a target bilateral trade matrix representing the average over all traded goods is used.

When the monetary flows of the national input-output tables are supplemented with physical flow data on the emission-relevant fossil fuel use in production sectors and final demand, the implicit price for the same fuel varies substantially across different sectors and countries. In applied economic model-building the common approach is to ignore these differences and assume uniform prices for fuels across users. The latter assumption involves an ad hoc scaling of sector-specific and energy-specific CO_2 coefficients in order to obtain official figures on the total national carbon emissions. The problem with this shortcut is that CO_2 coefficients are then not based on actual energy flows, and the implicit marginal abatement cost curves can be significantly in error. We therefore use physical energy flows and energy prices as reported in energy statistics, rather than aggregate input-output monetary values.

Finally, we perform a forward calibration of our model to 2010 incorporating the European Commission's exogenous baseline assumptions on GDP growth, world energy prices, changes in the fossil fuel mix for electricity generation, and energy (carbon) efficiency improvements over time. Böhringer, Jensen and Rutherford [2000] provide a detailed description of this forward projection.