3. Economic impacts of carbon abatement strategies

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1. INTRODUCTION

Despite the withdrawal of the USA under President Bush in March 2001, the Kyoto Protocol marks a milestone in climate policy history. For the first time, industrialized countries as listed in Annex B of the Protocol have agreed on quantified emissions limitations and reduction objectives. The negotiations around the Protocol have been dominated by two fundamental issues whose reconciliation is crucial for any substantial international agreement on climate protection: efficiency in terms of overall abatement costs, and equity in terms of a 'fair' distribution of these costs across countries. These issues are relevant in other fields of international environmental policy as well, but their importance in the greenhouse context is unique, given the potential magnitude of abatement costs at stake.

With regard to efficiency, the Kyoto Protocol allows for the use of emissions trading, joint implementation (JI) or the clean development mechanism (CDM) in order to reduce total costs of abatement. However, the permissible scope and institutional design of these flexible instruments are controversial among signatory parties. Several Annex B parties, such as the EU, are concerned that the extensive use of flexible instruments will negatively affect the environmental effectiveness of the Kyoto Protocol.

They stress the principle of supplementarity and call for ceilings on the amount by which national reduction targets can be achieved through the use of flexible instruments foreseen by the Kyoto Protocol (Baron et al. 1999). Other Annex B parties, such as the USA, have been strongly opposed to any ceiling plans throughout the negotiations.

With respect to equity, the Convention on Climate Change states that 'Parties should protect the climate system ... on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities' (UNFCCC 1997, Article 3.1). The Kyoto Protocol backs this proposition, though concepts of equity have remained rather vague during the negotiation process. Industrialized countries and economies in transition – both referred to as Annex B countries – have committed themselves to reducing greenhouse gas emissions to varying degrees, apparently meaning to reflect differences in the 'ability to pay'. Equity has also been invoked to justify the fact that developing countries have, as yet, not made any commitment to greenhouse gas abatement because they carry only minor historical responsibility for the increase of global greenhouse concentrations in the atmosphere.

A naïve assessment of the Kyoto Protocol may suggest that the adoption of concrete reduction commitments for Annex B countries reflects a careful balancing of efficiency and equity issues. However, the subsequent controversial Conferences of Parties, as well as the fact that no Annex B country has ratified the Protocol so far, indicate the opposite. Policy makers are obviously aware that the concrete – yet undefined – implementation of the Protocol will have important implications for the magnitude and regional distribution of compliance costs. Unresolved policy questions surrounding the implementation of the Kyoto Protocol deal with the implications of flexibility on the economic costs of abatement for Annex B countries, international spillovers to non-abating regions and global environmental effectiveness. Answers to these questions demand quantitative assessment, i.e. the use of analytical economic models. Obviously, models of complex socio-economic systems require simplifying assumptions on system boundaries and system relationships. These assumptions determine the model results and the derived policy conclusions. A major challenge of economic modeling is, therefore, to capture the key entities and relationships of the policy issue at hand. Given some inevitable ambiguity in this process, a careful check of the underlying assumptions is necessary: how do differences in perspectives affect the outcome and what are the implications for the choice of policy options?

There is meanwhile an extensive literature providing quantitative evidence on the economic effects of the Kyoto Protocol. Various studies have been incorporated into recent summary reports (Weyant 1999, IPCC 2001) with the explicit goal of identifying policy-relevant insights and providing explanations for differences in model results. While this is an important contribution, one major shortcoming remains: the models underlying the economic analysis still come as black boxes to non-expert readers. Without knowing the theoretical model, all they can do is believe or not believe the numerical results. Our modest objective here is to open this black box to some extent. We introduce a generic analytical framework which can address the economic and environmental implications of emission abatement strategies in a consistent way. Key features of the model are motivated by the nature of economic issues surrounding carbon abatement policies. Applications to open questions of the Kyoto Protocol will demonstrate how the model can be used for policy analysis, and complementary sensitivity analysis will identify the importance of the key assumptions underlying our calculations.

This chapter is organized as follows: Section 2 provides a short summary of relevant policy issues and presents the main results from applied modeling. Section 3 discusses in further detail computable general equilibrium (CGE) models, which have become the prevailing approach for the economy-wide analysis of climate policy measures. We will outline a blueprint of a comparative-static multi-region, multi-sector CGE model designed for the analysis of alternative Kyoto implementation policies. Section 4 provides applications of this model to selected issues of the international climate policy debate. Section 5 summarizes and concludes.

2. POLICY ISSUES

An economic assessment of climate change has to make a trade-off between costs and benefits. More specifically, rational climate policy making should weigh the benefits from avoided undesirable consequences of global warming against the costs of greenhouse gas emission abatement. To this end, the established technique of cost–benefit analysis (see e.g. Mishan 1975, Maddison 1995, Pearce 1998) provides the appropriate framework for measuring all negative and positive policy impacts and resource uses in the form of monetary costs and benefits. An economically efficient policy for emissions reduction maximizes net benefits, i.e. the benefits of slowed climate change minus the associated costs of emissions reductions. Net benefit maximization requires that emissions reduction efforts are taken up to the level where the marginal benefit of reduced warming equals the marginal cost of emissions reduction.

Given complete information, cost–benefit analysis could tell us how much greenhouse gas (GHG) emissions should be abated, when and by whom. However, neither costs nor benefits of GHG abatement are easy to quantify. In particular, there are large uncertainties in external cost estimates for climate change. The chain of causality – from GHG emissions to ambient concentrations of GHGs in the atmosphere, from temperature increase to physical effects such as climatic and sea level changes – is highly complex. Little agreement exists, therefore, on the desirable level of greenhouse gas emission concentrations in the atmosphere and the scope and timing of emission mitigation measures.

The large uncertainties in external cost estimates are reflected in the current climate policy debate. Emissions reduction objectives are not the outcome of a rigorous cost–benefit analysis, but must rather be seen as a first response to recommendations from natural science on tolerable emission levels. In this vein, we restrict our subsequent analysis of emission abatement strategies to a cost-effectiveness approach. Cost-effectiveness analysis aims at identifying the least expensive way of achieving a given environmental quality target.[1] Only the costs are assessed in relation to an environmental goal; the policy target which represents the level of benefits is taken as given. In climate policy, targets may be formulated with respect to different bases, such as the stabilization of GHG emissions in a certain year, a long-run stabilization of atmospheric concentrations of particular greenhouse gases or the prevention of physical consequences (e.g. sea level rise). For the cost-effectiveness analysis in Section 4, we simply adopt the short-term GHG emissions reduction targets as formulated in the Kyoto Protocol. That is, we measure the economic costs of alternative policy strategies to meet the emissions reduction objectives which Annex B countries have committed to.

In the remainder of this section, we address key issues in the climate policy debate and summarize evidence from quantitative studies without discussing the details of the underlying models. Our objective is twofold. First, we want to justify the choice of the analytical framework described in Section 3. Secondly, we want to motivate the choice of policy scenarios and the design of sensitivity analysis, both of which are discussed in detail in Section 4. For the reasons mentioned, we do not enter the scientific debate on the benefits associated with GHG emissions reduction. Starting from some exogenous global emissions reduction objective, the policy debate comes down to the magnitude and the distribution of abatement costs across regions for alternative policy strategies. The ongoing negotiations around the Kyoto Protocol provide a prime example of the issues at stake. Individual contributions of the Annex B Parties to the Protocol were determined by two basic considerations. On the one hand, the potential costs of the committed reduction had to be ‘sufficiently low’. Even voters in wealthy industrialized countries reveal a rather modest willingness to pay for climate protection whose benefits are unclear and of long-term nature (Böhringer and Vogt 2001). On the other hand, the expected pattern of costs across Parties had to comply with basic fairness principles (see e.g. Lange and Vogt 2001). The latter inevitably involves ethically-based equity criteria (see IPCC 1996 and 2001).

The standard approach of positive economics is to separate efficiency and equity considerations. Economics cares for the minimization of the total costs to reach some exogenous reduction target. It is then left to other disciplines as to how these costs should be allocated across agents through lump-sum transfers in order to meet some equity criteria. In the structure of this section, we will take up the traditional distinction between efficiency and equity issues. It should be noted, however, that both issues are closely linked when lump-sum instruments are not available, which is typically the case in political practice.

Our short summary is far from being comprehensive. The informed reader will notice that we have omitted several topics which are not necessarily less important than those explicitly addressed. Among these topics are offsets from CO_2 sinks (see Reilly et al. 1999, Stavins 1999), the incorporation of non-CO_2 GHG mitigation options (see MacCracken et al. 1999, Burniaux and Martins 2000, Reilly et al. 1999), implications from intertemporal flexibility (see Richels and Sturm 1996, Richels et al. 1996, Tol 1999), and quantitative limits to trade (see Criqui et al. 1999, Ellerman and Wing 2000).

2.1 The Magnitude of Abatement Costs

People who search for empirical evidence on the economic impacts of GHG abatement policies are often puzzled about the diverging results across quantitative studies. Not only are there differences in the order of magnitude for abatement costs, but also the sign in reported costs may be opposite. In other words, while one study suggests that an abatement policy results in economy-wide losses, another one indicates economic gains. This ‘battle over numbers’ explains reservations with respect to the usefulness of quantitative modeling. The constructive approach to this problem is not to renounce insights from applied modeling but to develop some understanding of differences in results. Most of these differences can be traced back to different assumption on the status quo, i.e. the baseline, of the economic system without exogenous policy interference (see Section 2.1.1). Another major source for deviations in cost estimates are differences in the scope of economic interactions that are captured by the studies (see Section 2.1.2). The awareness of these determinants for economic impacts of exogenous policy changes is a prerequisite to properly understanding model results and drawing appropriate conclusions (Böhringer 1999). Hence, a major task for applied modeling is to reveal the importance of subjective judgements, which are implicit in the choice of the baseline, system boundaries and system relationships, for quantitative model results by means of sensitivity analysis.

2.1.1 Baseline assumptions

2.1.1.1 Projections The economic effects of future emission constraints depend crucially on the extent to which quantified emission limitation and reduction objectives will bind the respective economies. In other words, the magnitude of costs associated with the implementation of future emission constraints depends on the Business-as-Usual (BaU) projections for GDP, fuel prices, energy efficiency improvements etc. High economic growth alone, for example, leads to high energy demands and emissions. In the context of the Kyoto Protocol, 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. The importance of baseline projections generally receives little attention in the literature. Most modelers are typically careful in specifying their BaU assumptions but they rarely report results from sensitivity analyses. One exception is Böhringer, Jensen and Rutherford (2000), who study the implications of alternative baseline projections on the magnitude and distribution of emission abatement costs under the Kyoto Protocol within the EU.

2.1.1.2 Market imperfections The incorporation of existing market imperfections is a key factor in explaining why economic adjustments towards more stringent emission constraints might lead to economic gains even when we ignore the benefits of avoided GHG emissions. If policy measures induce reactions that weaken existing distortions, the net outcome might be beneficial even if the policy measure standing alone, i.e. without initial market imperfections, were to cause economic adjustment costs. In the climate change debate, this phenomenon is sometimes referred to as a no-regrets option for abatement policies.

No-regrets options are, by definition, actions to reduce GHG emissions that have negative net costs because they generate direct or indirect benefits large enough to offset their implementation costs. The existence of no-regrets potentials implies that market forces are not operating perfectly. Market imperfections may be due to imperfect information, lack of competition or distortionary fiscal systems and limited financial markets. It should be noted, however, that the removal of market failures and market barriers can cause significant transaction costs (Grubb et al. 1993). Taking transaction costs into account, no-regrets options may be significantly reduced or even non-existent (see Jaffe and Stavins 1991). This explains why economists are rather skeptical about the magnitude of the no-regrets options reported in bottom-up technology-based studies (Krause et al. 1999). These studies assume large initial 'efficiency gaps' between the best available technologies and the equipment actually in use, but they do not incorporate the transaction costs of removing these inefficiencies.

The debate on a double dividend from environmental regulation also builds on the notion of no-regrets policies. Instruments such as carbon taxes or auctioned tradable permits generate revenues to the government. If these revenues are used to reduce existing tax distortions, emission abatement policies may yield a double dividend, i.e., simultaneously improve environmental quality (first dividend) and offset at least part of the welfare losses of climate policies by reducing the overall costs of raising public funds (second dividend). The literature distinguishes two forms of double dividend (Goulder 1995b). In its weak form, a double dividend occurs as long as the gross costs of environmental policies are systematically lower when revenues are recycled via cuts in existing distortionary taxes, rather than being returned as a lump sum. In its strong form, the existence of a double dividend requires that the net cost of the environmental policy is negative (for theoretical analyses see Goulder 1995b or Bovenberg 1999). The weak double dividend is confirmed by many theoretical and numerical studies (e.g. EMF-16 1999). Evidence on the strong double dividend is rather mixed. In public finance terms, a strong double dividend occurs when the marginal distortionary effect of a carbon tax is lower than the marginal distortionary effect of the substituted taxes, given some constant level of tax revenues (Hourcade and Robinson 1996). The existence of a strong double dividend thus depends on a number of factors, such as pre-existing inefficiencies of the tax system along non-environmental dimensions, the type of tax cuts (reductions in payroll taxes, value added taxes (VAT), capital taxes, or other indirect taxes), labor market conditions (level of unemployment and functioning of labor markets), the method of recycling and the level of environmental taxes (i.e. the environmental target). Environmental taxes may well exacerbate rather than alleviate pre-existing tax distortions. This is because environmental taxes induce not only market distortions similar to those of the replaced taxes but also new distortions in intermediate and final consumption. The negative impacts from levying additional environmental taxes (tax interaction effect) can dominate the positive impacts of using additional revenues for cuts in existing distortionary taxes (revenue recycling effect). This result is suggested by the stylized numerical and theoretical studies of Bovenberg and de Mooij (1994) and Parry et al. (1999). Applied studies of economies with few distortions such as the USA find no strong double dividend, but cost reductions as compared to lump-sum recycling up to 30 to 50 per cent (Jorgenson and Wilcoxen 1993, Goulder 1995a). Complementary analysis for EU countries with more distortionary tax systems and substantial labor market imperfections are more optimistic on the prospects for a strong double dividend (Barker 1998 and 1999). In general, it can be argued that existing market imperfections provide an opportunity for beneficial policy reforms independent of environmental policies. In this vein, the second dividend may not be fully attributable to environmental regulation. On the other hand, the taxation of pollution can be seen as a second-best instrument, given growing political constraints on traditional non-environmental taxes (Hourcade 1993).

2.1.2 System boundaries

The choice of system boundaries determines the extent to which the cost-effectiveness analysis accounts for policy-induced adjustment costs. The main challenge of modeling is to select only those system elements and their relationships which really matter for the question at hand. To put it differently: the exclusion of cost components that are outside the chosen system boundaries should not significantly affect the order of magnitude of quantitative results nor the ranking of alternative policy options. In modeling practice, this rule of thumb can hardly be kept because one often does not know beforehand if simplifications that are, after all, a key element of modeling, may turn out to be too simple. Obviously, there is a trade off between the scope of the system to be captured and the level of detail. In our discussion of system boundaries, we start with the widespread distinction between energy-system analysis (bottom-up) and macroeconomic impact analysis (top-down) of emission abatement strategies. Another important issue in the choice of system boundaries is the degree to which international spillovers from domestic policies are taken into account. The common distinction made here is between single-country models and multi-region models. Finally, we point out that system boundaries do not necessarily have a spatial or temporal dimension, but refer – more generally – to the degree of adopted endogeneity for system relationships. We illustrate the latter in the discussion of technological change.

2.1.2.1 Bottom-up versus top-down There are two broad approaches for modeling the interaction between energy, the environment and the economy. They differ mainly with respect to the emphasis placed on (1) a detailed, technologically based treatment of the energy system, and (2) a theoretically consistent description of the general economy. The models placing emphasis on (1) are purely partial models of the energy sector, lacking interaction with the rest of the economy.[2] In general, they are bottom-up engineering-based linear activity models with a large number of energy technologies to capture substitution of energy carriers on the primary and final energy level, process substitution, process improvements (gross efficiency improvement, emission reduction) or energy savings. They are mostly used to compute the least-cost method of meeting a given demand for final energy or energy services subject to various system constraints such as exogenous emission reduction targets. The models emphasizing (2) are general economic models with only rudimentary treatment of the energy system. Following the top-down approach, they describe the energy system (similar to the other sectors) in a highly aggregated way by means of neoclassical production functions, which capture substitution possibilities by means of substitution elasticities. These models may be classified as open (demand driven Keynesian) or closed (general equilibrium) models (for a model classification see for example Weyant 1999) and capture feedback effects of energy policies on non-energy markets such as price changes for factors or intermediate goods.

In the literature it is often overlooked that the differences between top-down models and bottom-up models are less of a theoretical nature; rather, simply relate to the level of aggregation and the scope of *ceteris paribus* assumptions.[3]

2.1.2.2 International spillovers Since world economies are increasingly linked through international trade, capital flows and technology transfers, emission abatement by one country has spillovers on other countries. In the policy debate over climate change, spillovers from Annex B countries' abatement to non-abating developing countries play an important role. The Kyoto Protocol explicitly acknowledges the importance of international spillovers in stipulating that unilateral abatement policies should minimize adverse trade effects on developing countries (UNFCCC 1997, Article 2.3). Even more, the UNFCCC guarantees compensation by Annex B to the developing world for induced economic costs under Articles 4.8 and 4.9. On the other hand, the developed Annex B countries fear adverse impacts from unilateral abatement, because their energy use will be taxed, while there will be no taxes in the developing world, hence they can expect to lose competitiveness in energy-intensive production. In a more dynamic perspective, important spillovers may also stem from technology transfers. In the presence of induced technological change, cleaner technologies developed as a response to abatement policies in industrialized countries may diffuse internationally, generating positive spillovers for non-abating countries. The diffusion of cleaner technologies may offset some or all of the negative leakage effects (Grubb 2000). Environmental implications of international spillovers concern the phenomenon of carbon leakage due to sub-global action, which may have important consequences for the design of unilateral abatement strategies (Böhringer, Rutherford and Voss 1998). The following paragraphs discuss the implications of spillovers on regional adjustment costs, industrial competitiveness and global environmental effectiveness in more detail.

Carbon abatement in large open economies not only causes adjustment of domestic production and consumption patterns, but it also influences international prices via changes in exports and imports. Changes in international prices, i.e. the terms of trade (TOT),[4] imply a secondary benefit or burden that can significantly alter the economic implications of the primary domestic policy.[5] Some countries may shift part of their domestic abatement costs to trading partners, while other abating countries face welfare losses from a deterioration of their terms of trade.

With respect to the aggregate terms-of-trade effects, the most important are changes in international fuel markets. The cutback in global demand for fossil fuels due to carbon emission constraints implies a significant drop of their prices, providing economic gains to fossil fuel importers and losses to fossil fuel exporters (van der Mensbrugghe 1998, Tulpulé et al. 1999, McKibbin et al. 1999, Bernstein et al. 1999, Montgomery and Bernstein 2000, Böhringer and Rutherford 2001).

The economic implications of international price changes on non-energy markets are more complex. Higher energy costs implied by carbon taxes raise the prices of non-energy goods (in particular energy-intensive goods) produced in abating countries. Countries that import these goods suffer from higher prices to the extent that they cannot substitute them with cheaper imports from non-abating countries. The ease of substitution – captured by the Armington elasticity – not only determines the implicit burden shifting of carbon taxes via non-energy exports from abating countries, but also the extent to which non-abating countries achieve a competitive advantage *vis-à-vis* abating exporters. The gain in market shares due to substitution effects may be partially offset by an opposite scale effect: due to reduced economic activity and income effects, import demand by the industrialized world declines, and this exerts a downward pressure on the prices of developing country exports. On average, non-abating regions or countries with very low carbon taxes gain comparative advantage on non-energy markets that, however, may not be large enough to offset potentially negative spillovers from international fuel markets.

Terms-of-trade changes affect the pattern of comparative advantage. This refers to the relative cost of producing goods in a particular country compared to the relative cost of producing these goods elsewhere. Since, in the neoclassical view, the location of production is determined by these relative cost differences, competitiveness and comparative advantage can be used interchangeably. Carbon taxes increase production costs and reduce international competitiveness, depending on the size of the carbon tax and the carbon intensity of the product. Particularly, energy-intensive industries such as chemicals, steel or cement in mitigating countries are negatively affected. However, surveys on the impacts of carbon abatement policies on international competitiveness have found only minor effects so far, which might be due to rather modest emission taxes and wide-ranging exemption schemes for energy-intensive production (Ekins and Speck 1998 and Barker and Johnstone 1998). The use of flexibility instruments reduces the competitive advantage of non-Annex B countries (Böhringer and Rutherford 2001; see also Section 4.2.2).

Sub-global abatement may lead to an increase in emissions in non-abating regions, reducing the global environmental effectiveness. This phenomenon is referred to as ‘leakage’. Emission leakage is measured as the increase in non-Annex B emissions relative to the reduction in Annex B emissions. There are three basic channels through which carbon leakage can occur. First, leakage can arise when, in countries undertaking emission limitations, energy-intensive industries lose in competitiveness and the production of emission-intensive goods relocates, raising emission levels in the non-participating regions (trade channel). Secondly, cut-backs of energy demands in a large region due to emission constraints may depress the demand for fossil fuels and thus induce a significant drop in world energy prices. This, in turn, could lead to an increase in the level of demand (and its composition) in other regions (energy channel). Thirdly, carbon leakage may be induced by changes in regional income (and thus energy demand) due to terms of trade changes (Rutherford 1995b). Leakage rates reflect the impact of sub-global emission abatement strategies on comparative advantage. Model-based results on carbon leakage depend crucially on the assumed degree of substitutability between imports and domestic production in the formulation of international trade (see for example Böhringer, Ferris and Rutherford 1998, Böhringer 1998a). Other major factors influencing the leakage rates are the assumed degree of competitiveness in the world oil market, the supply elasticities of fossil fuels, the substitution elasticity between energy and other inputs in the production of abating regions and the level of emissions trading (see Oliveira-Martins et al. 1992, Pezzey 1992, Manne and Oliveira-Martins 1994, Bernstein et al. 1999, Burniaux and Martins 2000 and Paltsev 2000a).

2.1.3 Technological change

Technological change is an important determinant of the economic costs induced by mid- and long-run GHG emission constraints, as it may significantly alter production possibilities over time. Löschel (2001) provides an overview of how technological change is represented in applied environment-economy models. These usually account for technical progress through an exogenous technical coefficient called the autonomous energy efficiency improvement (AEEI) (e.g. Capros et al. 1997).[6] The AEEI reflects the rate of change in energy intensity, i.e. the ratio of energy consumption over gross domestic product, holding energy prices constant (IPCC 1996). It is a measure of all non-price induced changes in gross energy intensity, including technical developments that increase energy efficiency, as well as structural changes. The higher (lower) the AEEI, the lower (higher) the baseline emissions, and the lower (higher) the costs to reach a climate target relative to a given base year. Estimates for AEEI rates range from 0.4 per cent to 1.5 per cent (Dean and Hoeller 1992, Kram 1998 and Weyant 1998). Sensitivity studies demonstrate the crucial importance of the AEEI parameter. Even small differences in the number chosen for the AEEI result in large differences in energy demand and emissions in the baseline and, hence, the total costs of emissions reductions (Manne and Richels 1990 and 1992).

The implication of the treatment of technological change using AEEIs in prevalent models is that technological progress is assumed to be invariant with respect to climate policy interference. The modeling of the rate and direction of technical change in climate policy models as exogenous must be considered as a severe limitation (Anderson 1999). If climate policies lead to improvements in technology, then the total costs of abatement may be substantially lower as compared to results from conventional models with exogenous technical change. However, at present, the theory of induced technological change (ITC) is still in development. The main elements in models of technological innovation are (1) corporate investment such as research and development (R&D) as well as learning by doing (LBD) in response to market conditions, and (2) spillovers from R&D. Innovation as a product of explicit private investment incentives in the knowledge sector has its origin in firm level innovation theory, which focuses on private profit incentives from (at least partly) appropriable innovations. With learning by doing in technologies, the technology costs are modeled explicitly as a function of cumulative investment or of installed capacity in that technology. Spillover effects stem from macro-level endogenous or 'new' growth theory. Investments in human capital and technology result in positive externalities (spillovers).

Investment in R&D is presented in models by Goulder and Schneider (1999), Buonanno et al. (2000) and Goulder and Mathai (2000). Quantitative results from these models indicate only weak impacts of induced technical change on the gross costs of abatement. Concerning LBD, it is found that marginal returns from LBD vary greatly between industries at different stages of development. For example, learning-by-doing effects in the mature conventional energy industries may be rather small compared to renewable energy industries (Anderson 1999, Goulder and Mathai 2000). Knowledge spillovers from R&D are analyzed by Goulder and Schneider (1999), Weyant and Olavson (1999) and Goulder and Mathai (2000). They found that R&D market failures (knowledge spillovers) justify R&D subsidies as a second policy instrument in addition to a carbon tax. A counter-example is given by Kverndokk et al. (2000).

With endogenous technological change, the derivation of the shape of the least-cost mitigation pathway becomes more complex (Grubb 1997).[7] ITC from investments in R&D makes it preferable to concentrate more abatement efforts in the future since it lowers the relative costs of future abatement. Early emissions-reduction measures are more preferable when LBD is considered, since current abatement contributes to a learning process that reduces the costs of future abatement (Goulder and Mathai 2000).

2.2 Equity: Burden Sharing

The establishment of international trade in emission rights requires a decision on the initial allocation of these emission rights among nations. From the Coase Theorem we know that the allocation of permits and the implied wealth transfer have only minor effects on the global costs of abatement. When trading concludes, each country will hold the economically efficient (cost-effective) amount of permits (i.e. marginal abatement costs across countries will be equalized), independent of the initial allocation of permits (Manne and Richels 1995). However, the initial allocation of emission rights has major effects on the distribution of gains and losses and thus on the perceived equity of the agreement. Since there is no unique definition of equity or the objectives to which it should be applied, it is a political issue that requires the solution of serious political differences on burden sharing between industrialized countries on the one hand, and between developed and developing countries on the other hand.

Several alternative equity criteria can be found in the literature (see Kverndokk 1995, Rose and Stevens 1998 and Rose et al. 1998): under the egalitarian criterion it is assumed that all nations have an equal right to pollute or be protected from pollution. Emission rights are distributed in proportion to current emissions ('grandfathered'). Under the egalitarian fairness criterion, all people have an equal right to pollute or be protected from pollution. Emission rights are allocated in proportion to population ('equal per capita emissions'). The no-harm criterion states that some (poor) nations should not incur costs. Emission rights are distributed to these countries according to their baseline emissions. The Kyoto Protocol may be seen as yet another *ad hoc* equity criterion. The differentiation in commitments follows some implicit equity considerations (UNFCC 1997, Article 3.1).

There are several modeling studies that analyze the effects of different schemes for allocating emission rights (Manne and Richels 1995, Edmonds et al. 1995, Rose and Stevens 1998, Rose et al. 1998, Böhringer, Harrison and Rutherford, forthcoming and Böhringer and Welsch 1999). Most of these studies deal with global abatement strategies beyond Kyoto and impose emission constraints on developing countries to assure long-term reduction of global GHG emissions. A robust policy conclusion from these studies is that the problem of burden sharing implicit in alternative permit allocation schemes (i.e. equity rules) will be significantly relaxed through efficiency gains from world-wide emissions trading. Complementary analysis suggests that for very different allocations of emission rights, essentially the same cost pattern emerges when efficiency gains from trade in emission rights are not distributed via the market mechanism, but instead according to rules derived from fair division theory (Böhringer and Helm 2001). The latter may be far less controversial than equity rules applied to the initial allocation of emission rights.

The separability of efficiency and equity under marketable permits allows us to concentrate on the former in our model simulations in Section 4. Equilibrium abatement costs are unaffected by different permit distributions. However, as was previously pointed out, in international treaties such as the Kyoto Protocol, equity considerations may be crucial (Rose 1990). The pursuit of equity consideration may even promote efficiency, since more parties with relatively lower abatement costs may be enticed into the agreement if it is perceived to be fair, which, in the case of many developing countries, may be an equal per capita allocation of permits (see for example Morrisette and Plantinga 1991, Bohm and Larsen 1994).

3. A GENERIC CGE MODEL FOR CARBON ABATEMENT POLICY ANALYSIS

Carbon abatement policies not only cause direct adjustments of fossil fuel markets, but they produce indirect spillovers to other markets that, in turn, feed back to the economy. General equilibrium provides a consistent framework for studying price-dependent interactions between the energy system and the rest of the economy. The simultaneous explanation of the origin and spending of the income of the economic agents makes it possible to address both economy-wide efficiency as well as the equity implications of abatement policy interference. Therefore, computable general equilibrium (CGE) models have become the standard tool for the analysis of the economy-wide impacts of greenhouse gas abatement policies on resource allocation and the associated implications for incomes of economic agents (Bergmann 1990, Grubb et al. 1993, Weyant 1999).[8]

This section outlines the main characteristics of a generic static general equilibrium model of the world economy designed for the medium-run economic analysis of carbon abatement constraints (see Böhringer and

Rutherford 2001). It is a well-known Arrow-Debreu model that concerns the interaction of consumers and producers in markets. Consumers in the model have a primary exogenous endowment of the commodities and a set of preferences giving demand functions for each commodity. The demands depend on all prices; they are continuous and non-negative, homogeneous of degree zero in factor prices and satisfy Walras' Law, i.e. the total value of consumer expenditure equals consumer income at any set of prices. Market demands are the sum of final and intermediate demands. Producers maximize profits given constant returns to scale production technology. Because of the homogeneity of degree zero of the demand functions and the linear homogeneity of the profit functions in prices, only relative prices matter in such a model. Two classes of conditions characterize the competitive equilibrium in the model: market clearance conditions and zero profit conditions. In equilibrium, price levels and production levels in each industry are such that market demand equals market supply for each commodity. Profit maximization under constant returns to scale technology implies that no activity does any better than break even at equilibrium prices (Shoven and Whalley 1984). The model is a system of simultaneous, non-linear equations with the number of equations equal to the number of variables.

The concrete specification of the model, with respect to the impact analysis of the Kyoto Protocol, covers 11 regions, eight sectors and three factors. The regional aggregation includes Annex B parties as well as major non-Annex B regions that are central to our analysis. Our model thus accounts for potential terms-of-trade effects triggered by carbon abatement policies. The sectoral aggregation in the model has been chosen to distinguish carbon-intensive sectors from the rest of the economy as far as possible given data availability. It captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across carbon-intensive goods. The energy goods identified in the model are coal, natural gas, crude oil, refined oil products and electricity. The non-energy sectors include important carbon-intensive and energy-intensive industries that are potentially most affected by carbon abatement policies, such as transportation services and an aggregate energy-intensive sector. The rest of the economy is divided into other machinery, construction and other manufactures and services. The primary factors in the model include labor, physical capital and fossil-fuel resources. Factor markets are assumed to be perfectly competitive. In our baseline scenario, labor and physical capital are treated as perfectly mobile across sectors. Fossil-fuel resources are sector-specific. All factors are immobile between regions. Table 3.1 summarizes the regional, sectoral, and factor aggregation of the model.

3.1 Production

Within each region (indexed by the subscript *r*), each producing sector (indexed interchangeably by *i* and *j*) is represented by a single-output producing firm which chooses input and output quantities in order to maximize profits. Firm behavior can be construed as a two-stage procedure in which the firm selects the optimal quantities of primary factors *k* (indexed by *f*) and intermediate inputs *x* from other sectors in order to minimize production costs, given input prices and some production level *Y*, with $Y = \varphi\ (k,x)$ the production functions. The second stage, given an exogenous output price, is the selection of the output level *Y* to maximize profits. The firm's problem is then:

$$\underset{y_{jir},x_{jir},k_{fir}}{Max} \quad \Pi_{ir} = p_{ir} \cdot Y_{ir} - C_{ir}\left(p_{jr}, w_{fr}, Y_{ir}\right) \;\; s.t. \;\; Y_{ir} = \varphi_{ir}\left(x_{jir}, k_{fir}\right) \quad [3.1]$$

where Π denotes the profit functions, *C* the cost functions which relate the minimum possible total costs of producing *Y* to the positive input prices, technology parameters, and the output quantity *Y*, and *p* and *w* are the prices for goods and factors, respectively.

In the model, production of each good takes place according to constant elasticity of substitution (CES) production functions, which exhibit constant returns to scale. Therefore, the output price equals the per-unit cost in each sector, and firms make zero profits in equilibrium (Euler's Theorem).

Profit maximization under constant returns to scale implies the equilibrium condition:

$$\pi_{ir} = p_{ir} - c_{ir}(p_{jr}, w_{fr}) = 0 \quad \text{(zero profit condition)} \qquad [3.2]$$

where *c* and π are the unit cost and profit functions, respectively.

Demand functions for goods and factors can be derived by Shepard's Lemma. It suggests that the first-order differentiation of the cost function with respect to an input price yields the cost-minimizing demand function for the corresponding input.

Table 3.1 Model dimensions

Countries and Regions	
Annex B	
CEA	Central European Associates
EUR	Europe (EU15 and EFTA)
FSU	Former Soviet Union (Russian Federation and Ukraine)
JPN	Japan
OOE	Other OECD (Australia and New Zealand)
USA	United States
Non-Annex B	
ASI	Other Asia (except for China and India)
CHN	China (including Hong Kong and Taiwan)
IND	India
MPC	Mexico and OPEC
ROW	Rest of World
Production sectors	
Energy	
COL	Coal
CRU	Crude oil
GAS	Natural gas
OIL	Refined oil products
ELE	Electricity
Non-Energy	
AGR	Agricultural production
EIS	Energy-intensive sectors
OTH	Other manufactures and services
CGD	Savings good
Primary factors	
L	Labor
K	Capital
R	Fixed factor resources for coal, oil and gas

Hence, the intermediate demand for good *j* in sector *i* is:

$$x_{jir} = \frac{\partial C_{ir}}{\partial p_{jr}} = Y_{ir} \cdot \frac{\partial c_{ir}}{\partial p_{jr}} \qquad [3.3]$$

and the demand for factor *f* in sector *i* is:

$$k_{fir} = \frac{\partial C_{ir}}{\partial w_{fr}} = Y_{ir} \cdot \frac{\partial c_{ir}}{\partial w_{fr}} . \qquad [3.4]$$

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

$$x_{jir} = \frac{\partial \Pi_{ir}}{\partial p_{jr}} = Y_{ir} \cdot \frac{\partial \pi_{ir}}{\partial p_{jr}} \text{ and } k_{fir} = \frac{\partial \Pi_{ir}}{\partial w_{fr}} = Y_{ir} \cdot \frac{\partial \pi_{ir}}{\partial w_{fr}} . \qquad [3.5]$$

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

$$a^{x}_{jir} = \frac{\partial c_{ir}}{\partial p_{jr}} = \frac{\partial \pi_{ir}}{\partial p_{jr}} \text{ and } a^{k}_{fir} = \frac{\partial c_{ir}}{\partial w_{fr}} = \frac{\partial \pi_{ir}}{\partial w_{fr}} . \qquad [3.6]$$

The model captures the production of commodities by aggregate, hierarchical (or nested) CES production functions that characterize the technology through substitution possibilities between capital, labor, energy and material (non-energy) intermediate inputs (KLEM). Two types of production functions are employed: those for fossil fuels (*v* = COL, CRU, GAS) and those for non-fossil fuels (*n* = AGR, EIS, ELE, OIL, OTH).

Figure 3.1 illustrates the nesting structure in non-fossil fuel production. In the production of non-fossil fuels *nr,* non-energy intermediate inputs *M* (used in fixed coefficients among themselves) are employed in (Leontief) fixed proportions with an aggregate of capital, labor and energy at the top level.

At the second level, a CES function describes the substitution possibilities between the aggregate energy input *E* and the value-added aggregate *KL*:[9]

$$Y_{nr} = \min\left\{ \left(1-\theta_{nr}\right) M_{nr}, \theta_{nr}\phi_{nr} \left[\alpha_{nr} E_{nr}^{\rho^{KLE}} + \beta_{nr} KL_{nr}^{\rho^{KLE}} \right]^{1/\rho^{KLE}} \right\} \qquad [3.7]$$

with $\sigma^{KLE} = 1/(1\text{-}\rho^{KLE})$ the elasticity of substitution between energy and the primary factor aggregate and θ the input (Leontief) coefficient. Finally, at the third level, capital and labor factor inputs trade off with a constant elasticity of substitution σ^{KL} ($\sigma^{KL} = 1/(1\text{-}\rho^{KL})$):

$$KL_{nr} = \phi_{nr}\left[\alpha_{nr} K_{nr}^{\rho^{KL}} + \beta_{nr} L_{nr}^{\rho^{KL}}\right]^{1/\rho^{KL}} . \qquad [3.8]$$

As to the formation of the energy aggregate E, we employ several levels of nesting to represent differences in substitution possibilities between primary fossil fuel types as well as substitution between the primary fossil fuel composite and secondary energy, i.e. electricity. The energy aggregate is a CES composite of electricity and primary energy inputs FF with elasticity $\sigma^{E} = 1/(1\text{-}\rho^{E})$ at the top nest:

$$E_{nr} = \phi_{nr}\left[\alpha_{nr} ELE_{nr}^{\rho^{E}} + \beta_{nr} FF_{nr}^{\rho^{E}}\right]^{1/\rho^{E}} . \qquad [3.9]$$

The primary energy composite is defined as a CES function of coal and the composite of refined oil and natural gas with elasticity $\sigma^{COA} = 1/(1\text{-}\rho^{COA})$. The oil–gas composite is assumed to have a simple Cobb-Douglas functional form with value shares of oil and gas given by θ and $1\text{-}\theta$, respectively :

$$FF_{nr} = \phi_{nr}\left[\alpha_{nr} COA_{nr}^{\rho^{COA}} + \beta_{nr}\left(OIL^{\theta_{nr}} \cdot GAS^{1-\theta_{nr}}\right)^{\rho^{COA}}\right]^{1/\rho^{COA}} . \qquad [3.10]$$

Fossil fuel resources v are modeled as graded resources. The structure of production of fossil fuels is given in Figure 3.2. It is characterized by the presence of a fossil fuel resource in fixed supply. All inputs, except for the sector-specific resource R, are aggregated in fixed proportions at the lower nest. Mine managers minimize production costs subject to the technology constraint:

$$Y_{vr} = \phi_{vr}\left[\alpha_{vr} R_{vr}^{\rho_{vr}^{f}} + \beta_{vr}\left[\min\left(\theta_{vr}^{K} K_{vr}, \theta_{vr}^{L} L_{vr}, \theta_{vr}^{E} E_{vr}, \theta_{vr}^{M} M_{jvr}\right)\right]^{\rho_{vr}^{f}}\right]^{1/\rho_{vr}^{f}} \qquad [3.11]$$

The resource grade structure is reflected by the elasticity of substitution between the fossil fuel resource and the capital–labor–energy–material aggregate in production. The substitution elasticity between the specific factor and the Leontief composite at the top level is $\sigma_{vr}^{f} = 1/(1\text{-}\rho_{vr}^{f})$. This substitution elasticity is calibrated consistently with an exogenously given supply elasticity of fossil fuel ε_{vr} according to

$$\varepsilon_{vr} = \frac{1-\gamma_{vr}}{\gamma_{vr}}\sigma_{vr}^{f} \qquad [3.12]$$

with γ_{vr} the resource value share (Rutherford 1998). The resource value share represents major differences between fossil fuel sectors across regions. The resource cost share is rather high, e.g. in oil-exporting MPC, while its share is low in regions with less accessible resources (Babiker et al. 2001).

We now turn to the derivation of the factor demand functions for the nested CES production functions, taking into account the duality between the production function and the cost function. The total cost function that reflects the same production technology as the CES production function, for example, for value added *KL* in non-fossil fuel production given by [3.8], is:

$$C_{nr}^{KL} = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} \cdot KL_{nr} \qquad [3.13]$$

where PK and PL are the per-unit factor costs for the industry, including factor taxes if applicable. The price function for the value-added aggregate at the third level is:

$$PKL_{nr} = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} = c_{nr}^{KL}\,. \qquad [3.14]$$

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

$$\frac{K_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\alpha_{nr}\cdot\frac{PKL_{nr}}{PK_{nr}}\right)^{\sigma^{KL}}, \quad \frac{L_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\beta_{nr}\cdot\frac{PKL_{nr}}{PL_{nr}}\right)^{\sigma^{KL}} \qquad [3.15]$$

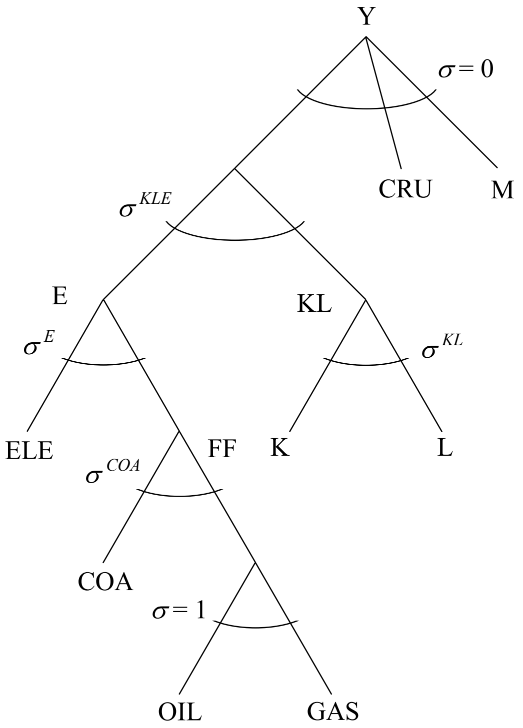

Figure 3.1 Nesting structure of non-fossil fuel production

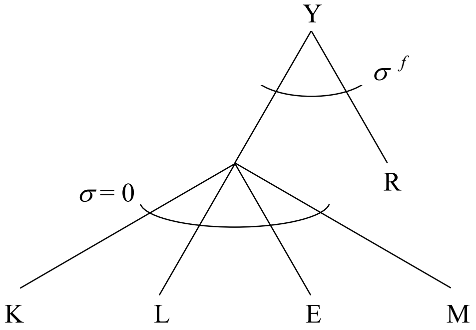

Figure 3.2 Nesting structure for fossil fuel production

In order to determine the variable input coefficient for capital and labor $a_{nr}^{K} = K_{nr} / Y_{nr}$ and $a_{nr}^{L} = L_{nr} / Y_{nr}$, one has to multiply

[3.15] with the per unit demand for the value added aggregate KL_{nr} / Y_{nr}, which can be derived in an analogous manner. The unit cost function associated with the production function [3.7] is:

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

[3.16]

and
$$\frac{KL_{nr}}{Y_{nr}} = \theta_{nr} \, \hat{\phi}_{nr}^{\sigma^{KLE}-1} \left(\hat{\beta}_{nr} \cdot \frac{PY_{nr}}{PKL_{nr}} \right)^{\sigma^{KLE}} \qquad [3.17]$$

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

$$a_{nr}^{L} = \theta_{nr} \, \phi_{nr}^{\sigma^{KL}-1} \, \hat{\phi}_{nr}^{\sigma^{KLE}-1} \left(\beta_{nr} \cdot \frac{PKL_{nr}}{PL_{nr}} \right)^{\sigma^{KL}} \left(\hat{\beta}_{nr} \cdot \frac{PY_{nr}}{PKL_{nr}} \right)^{\sigma^{KLE}} . \qquad [3.18]$$

3.2 Households

In each region, private demand for goods and services is derived from utility maximization of a representative household subject to a budget constraint given by the income level *INC*. The agent is endowed with the supplies of the primary factors of production (natural resources used for fossil fuel production, labor and capital) and tax revenues. In our comparative-static framework, overall investment demand is fixed at the reference level. The household's problem is then:

$$\underset{d_{ir}}{Max} \; W_r\left(d_{ir}\right) \;\; s.t. \;\; INC_r = \sum_{f} w_{fr} \bar{k}_{fr} + TR_r = \sum_{i} p_{ir} d_{ir} \qquad [3.19]$$

where W is the welfare of the representative household in region r, d denotes the final demand for commodities, $\bar{k}$ is the aggregate factor endowment of the representative agent and TR are total tax revenues. Household preferences are characterized by a CES utility function.

As in production, the maximization problem in [3.1] can thus be expressed in the form of a unit expenditure function e or welfare price index pw, given by:

$$pw_r = e_r\left(p_{ir}\right). \qquad [3.20]$$

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

$$d_{ir} = \overline{INC}_r \frac{\partial e_r}{\partial p_{ir}} \qquad [3.21]$$

with $\overline{INC}$ the initial level of expenditure.

In the model, welfare of the representative agent is represented as a CES composite of a fossil fuel aggregate and a non-fossil fuel consumption bundle. Substitution patterns within the latter are reflected via a Cobb-Douglas function. The fossil fuel aggregate in final demand consists of the various fossil fuels (*fe* = COL, OIL, GAS) trading off at a constant elasticity of substitution. The CES utility function is:

$$U_r = \left[\alpha_r \left(\sum_{fe} \beta_{fe,r} C_{fe,r}^{\rho^F} \right)^{\rho^C / \rho^F} + \phi_r \left(\prod_{j \notin fe} C_{jr}^{\theta_j} \right)^{\rho^C} \right]^{1/\rho^C} \qquad [3.22]$$

where the elasticity of substitution between energy and non-energy composites is given by $\sigma_C = 1/(1-\rho_C)$, the elasticity of substitution within the fossil fuel aggregate by $\sigma_{FE} = 1/(1-\rho_{FE})$, and θ_j are the value shares in non-fossil fuel consumption. The structure of final demand is presented in Figure 3.3.

Total income of the representative agent consists of factor income, revenues from taxes levied on output, intermediate inputs, exports and imports and final demand, as well as tax revenues from CO_2 taxes (TR) and a baseline exogenous capital flow representing the balance of payment deficits B less expenses for exogenous total investment demand $PI \cdot I$. The government activity is financed through lump-sum levies. It does not enter the utility function and is hence exogenous in the model. The budget constraint is then given by:

$$PC_r \cdot C_r = PL_r \cdot \overline{L}_r + PK_r \cdot \overline{K}_r + \sum_{v} PR_{vr} \cdot \overline{R}_{vr} + TR_r + \overline{B}_r - PI_r \cdot I_r \qquad [3.23]$$

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

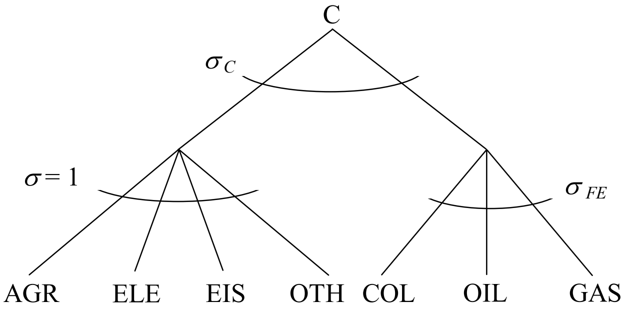

Figure 3.3 Structure of household demand

3.3 Foreign Trade

All commodities are traded in world markets. Crude oil and coal are imported and exported as a homogeneous product, reflecting empirical evidence that these fossil fuel markets are fairly integrated due to cheap shipping possibilities. All other goods are characterized by product differentiation. There is imperfect transformability (between exports and domestic sales of domestic output) and imperfect substitutability (between imports and domestically sold domestic output). Bilateral trade flows are subject to export taxes, tariffs and transportation costs and calibrated to the base year 1995. There is an imposed balance of payment constraint to ensure trade balance, which is warranted through flexible exchange rates, incorporating the benchmark trade deficit or surplus for each region.

On the output side, two types of differentiated goods are produced as joint products for sale in the domestic markets and the export markets respectively. The allocation of output between domestic sales *D* and international sales *X* is characterized by a constant elasticity of transformation (CET) function. Hence, firms maximize profits subject to the constraint:

$$Y_{ir} = \phi_{ir} \left[\alpha_{ir} D_{ir}^{\eta} + \beta_{ir} X_{ir}^{\eta} \right]^{1/\eta} \qquad [3.24]$$

with $\sigma^{tr} = 1/(1 + \eta)$ the transformation elasticity.

Regarding imports, the standard Armington convention is adopted in the sense that imported and domestically produced goods of the same kind are treated as incomplete substitutes (i.e. wine from France is different from Italian wine). The aggregate amount of each (Armington) good A is divided among imports and domestic production:

$$A_{ir} = \phi_{ir}\left[\alpha_{ir} D_{ir}^{\rho^D} + \beta_{ir} M_{ir}^{\rho^D}\right]^{1/\rho^D} . \qquad [3.25]$$

In this expression, $\sigma^D = 1/(1\text{-}\rho^D)$ is the Armington elasticity between domestic and imported varieties. Imports M are allocated between import regions s according to a CES function:

$$M_{ir} = \phi_{ir}\left[\sum_s \alpha_{ir} X_{isr}^{\rho^M}\right]^{1/\rho^M} \qquad [3.26]$$

with X the amount of exports from region s to region r and $\sigma^M = 1/(1\text{-}\rho^M)$ the Armington elasticity among imported varieties. Intermediate as well as final demands are, hence, (nested CES) Armington composites of domestic and imported varieties.

The assumption of product differentiation permits the model to match bilateral trade with cross-hauling of trade and avoids unrealistically strong specialization effects in response to exogenous changes in trade (tax) policy. On the other hand, the results may then be sensitive to the particular commodity and regional aggregation chosen in the model as indicated by Table 3.1 (Lloyd 1994).

3.4 Carbon emissions

GHGs and related gases have direct radiative forcing effects in the atmosphere. The various gases result from industrial production, fossil fuel consumption and household activities. The Kyoto Protocol includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) as gases subject to control.

We do not consider the abatement of a complete basket of GHG emissions from all energy-related sources as in the Kyoto Protocol, but instead, focus on carbon dioxide abatement from fossil fuel consumption, since it constitutes the largest part of the contribution to global warming. Carbon emissions are associated with fossil fuel consumption in production, investment, government and private demand. Carbon is treated as a Leontief (fixed coefficient) input into production and consumption activities. Each unit of a fuel emits a known amount of carbon, where different fuels have different carbon intensities. The applied carbon coefficients are 25 MT carbon per EJ for coal, 14 MT carbon per EJ for gas and 20 MT carbon per EJ for refined oil.

Carbon policies are introduced via an additional constraint that holds carbon emissions to a specified limit. The solution of the model gives a shadow value on carbon associated with this carbon constraint. This dual variable or shadow price can be interpreted as the price of carbon permits in a carbon permit system or as the CO_2 tax that would induce the carbon constraint in the model. The shadow value of the carbon constraint equals the marginal cost of reduction; it indicates the incremental cost of reducing carbon at the carbon constraint.

The total costs represent the resource cost or dead-weight loss to the economy of imposing carbon constraints. When reconciling different cost estimates, it should be noted that marginal cost is significant higher than average cost (Nordhaus 1991). Carbon emission constraints induce substitution of fossil fuels with less expensive energy sources (fuel switching) or employment of less energy-intensive manufacturing and production techniques (energy savings). The only means of abatement are hence inter-fuel and fuel-/non-fuel substitution or the reduction of intermediate and final consumption.

Given an emission constraint, producers as well as consumers must pay this price of the emissions resulting from the production and consumption processes. Revenues coming from the imposition of the carbon constraint are given to the representative agent. The total cost of Armington inputs in production and consumption that reflects the CES production technology in [3.25] but takes CO_2 emission restrictions into account is:

$$C_{ir}^{A} = \left[\left(\alpha_{ir}^{\sigma^{D}} PD_{ir}^{1-\sigma^{D}} + \beta_{ir}^{\sigma^{A}} PM_{ir}^{1-\sigma^{D}} \right)^{1/\left(1-\sigma^{D}\right)} + \tau_{r} \cdot a_{i} \right] \cdot A_{ir} \qquad [3.27]$$

with a_i the carbon emissions coefficient for fossil fuel i and τ the shadow price of CO_2 in region r associated with the carbon emission restriction:

$$\overline{CO2}_r = \sum_i A_{ir} \cdot a_i \qquad [3.28]$$

where $\overline{CO2}$ is the endowment of carbon emission rights in region r.

3.5 Zero Profit and Market Clearance Conditions

The equilibrium conditions in the model are zero profit and market clearance conditions. Zero profit conditions as derived in [3.2] require that no producer earns an 'excess' profit in equilibrium. The value of inputs per unit activity must be equal to the value of outputs. The zero profit conditions for production, using the variable input coefficient derived above, is:

$$PK \cdot a_{ir}^K \cdot Y_{ir} + PL \cdot a_{ir}^L \cdot Y_{ir} + \sum_j PA_j \cdot a_{jir}^M \cdot Y_{ir} = PY_{ir} \cdot Y_{ir} . \qquad [3.29]$$

The market clearance conditions state that market demand equals market supply for all inputs and outputs. Market clearance conditions have to hold in equilibrium. Domestic markets clear, equating aggregate domestic output plus imports, i.e. total Armington good supply, to aggregate demand, which consists of intermediate demand, final demand, investment and government demand:

$$A_{ir} = \sum_j Y_{jr} \frac{\partial \pi_{jr}^Y}{\partial PA_{ir}} + C_r \frac{\partial e_r}{\partial PA_{ir}} \qquad [3.30]$$

with PA the price of the Armington composite. π_{ir}^Z is the per unit profit function with Z the name assigned to the associated production activity. The derivation of π_{ir}^Z with respect to input and output prices, yields the compensated demand and supply coefficients, e.g. $\partial \pi_{jr}^Y / \partial PA_{ir} = a_{ijr}^A$, the intermediate demand for Armington good i in sector j of region r per unit of output Y. Output for the domestic market equals total domestic demand:

$$Y_{ir} \frac{\partial \pi_{ir}^Y}{\partial PD_{ir}} = \sum_j A_{jr} \frac{\partial \pi_{jr}^A}{\partial PD_{ir}} \qquad [3.31]$$

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

$$Y_{ir}\frac{\partial \pi_{ir}^{Y}}{\partial PX_{ir}} = \sum_{s} M_{is}\frac{\partial \pi_{is}^{M}}{\partial PX_{ir}} \qquad [3.32]$$

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

$$M_{ir} = A_{ir}\frac{\partial \pi_{ir}^{A}}{\partial PM_{ir}} \qquad [3.33]$$

where *PM* is the import price.

Primary factor endowment equals primary factor demand:

$$\overline{L}_{r} = \sum_{i} Y_{ir}\frac{\partial \pi_{ir}^{Y}}{\partial PL_{r}}, \qquad [3.34]$$

$$\overline{K}_{r} = \sum_{i} Y_{ir}\frac{\partial \pi_{ir}^{Y}}{\partial PK_{r}}, \qquad [3.35]$$

$$\overline{R}_{vr} = Y_{vr}\frac{\partial \pi_{vr}^{Y}}{\partial PR_{vr}}. \qquad [3.36]$$

An equilibrium is characterized by a set of prices in the different goods and factor markets such that the zero profit and market clearance conditions stated above hold.

3.6 Data and Calibration

The model is based on a Social Accounting Matrix (SAM), i.e. a comprehensive, economy-wide data framework, typically representing the economy of a nation (see, for example, Reinert and Roland-Holst 1997). The main data source underlying the model is the GTAP version 4 database that represents global production and trade data for 45 countries and regions, 50 commodities and five primary factors (McDougall 1998). In addition, we use OECD/IEA energy statistics (IEA 1996) for 1995. Reconciliation of these data sources yields the benchmark data of our model (see Babiker and

Rutherford 1997). For this application, the data set has been aggregated as shown in Table 3.1.

In order to perform simulations with our model, we need parameter values for the function parameters. Our large-scale model has many functional parameters that must be specified with relatively few observations. This prevents the econometric estimation of the model parameters as an econometric system of simultaneous equations. The estimation of the parameters using single-equation methods, on the other hand, would not produce an equilibrium solution for the model that matches the benchmark data. The conventional approach is to determine parameters for the equations in the model using a non-stochastic calibration method (Mansur and Whalley 1984). The model is calibrated to a single base-year equilibrium, such that the base solution to the model exactly reproduces the values of the adjusted data. Since we use CES utility and production functions, the assumptions of cost minimization and utility maximization leave us with one free parameter. Therefore, exogenously specified elasticity values from econometric literature estimates are also required. The other parameter values follow from the restrictions imposed by cost minimization and utility maximization. The given set of benchmark quantities and prices, together with the substitution elasticities given in Table 3.2, completely specify the benchmark equilibrium. The substitution elasticities determine the curvature of isoquants and indifference surfaces, while their position is given by the benchmark equilibrium data.

For example, consider again the value-added aggregate *KL* in non-fossil fuel production given by [3.8]. Deriving the first order conditions for cost minimization and solving for α gives:

$$\alpha_{nr} = \frac{PK_{nr} \cdot K_{nr}^{1/\sigma^{KL}} \Big/ PL_{nr} \cdot L_{nr}^{1/\sigma^{KL}}}{1 + PK_{nr} \cdot K_{nr}^{1/\sigma^{KL}} \Big/ PL_{nr} \cdot L_{nr}^{1/\sigma^{KL}}} \qquad [3.37]$$

with $PL = PL^* \ (1+tl\,)$ and $PK = \mathrm{PK}^* \ (1+tk)$ the cost of capital and labor including taxes *tl* and *tk*, respectively. Since benchmark data are given in value terms, we have to choose units for goods and factors to separate price and quantity observations. A commonly used units convention is to choose units for both goods and factors such that they have a price of unity in the benchmark. The benchmark net-of-tax factor prices *PL** and *PK** are thus set equal to one and [3.37] can be written as:

$$\alpha_{nr} = \frac{\left(1+tl_{nr}\right)\cdot K_{nr}^{1/\sigma^{KL}} \Big/ \left(1+tk_{nr}\right)\cdot L_{nr}^{1/\sigma^{KL}}}{1+\left(1+tl_{nr}\right)\cdot K_{nr}^{1/\sigma^{KL}} \Big/ \left(1+tk_{nr}\right)\cdot L_{nr}^{1/\sigma^{KL}}} \qquad [3.38]$$

The unit conventions further imply that the number of units of each factor equals the net of tax value of factor use. For each industry *n* the values of *L*, *tl*, *K* and *tk* are available from the underlying input–output tables and α can be calculated according to [3.38] given an exogenous value for the substitution elasticity σ^{KL} and thus ρ^{KL}. β_{nr} is (1 - α_{nr}). When we know α, β and ρ, we can calculate ϕ using the zero-profit condition:

$$PK_{nr}\cdot K_{nr} + PL_{nr}\cdot L_{nr} = KL_{nr} \qquad [3.39]$$

or

$$\phi_{nr} = \frac{\left(1+tk_{nr}\right)\cdot K_{nr} + \left(1+tl_{nr}\right)\cdot L_{nr}}{\left[\alpha_{nr} K_{nr}^{\rho^{KL}} + \beta_{nr} L_{nr}^{\rho^{KL}}\right]^{1/\rho^{KL}}}\,. \qquad [3.40]$$

In a second step, we do the forward calibration of the 1995 economies to the target year, which is 2010 in our case, employing baseline estimates by the US Department of Energy (DOE 1998) for GDP growth, energy demand and future energy prices. The economic effects of carbon abatement policies depend on the extent to which emissions reduction targets constrain the respective economies.

In other words, the magnitude and distribution of costs associated with the implementation of future emission constraints depend on the baseline (BaU) projections for GDP, fuel prices, energy efficiency improvements etc. In our comparative-static framework, we infer the BaU structure of the model regions for the target year using recent projections for economic development. We then measure the costs of abatement relative to that baseline.

Numerically, the model is formulated and solved as a mixed complementarity problem (MCP) using the Mathematical Programming Subsystem for General Equilibrium (MPSGE) described in Rutherford (1995a, 1999) within the Generalized Algebraic Modelling System (GAMS) mathematical modeling language (Brooke et al. 1996).

Table 3.2 Default values of key substitution and supply elasticities

Description	Value
Substitution elasticities in non-fossil fuel production	
σ^{KLE} Energy vs. value added	0.8
σ^{KL} Capital vs. labor	1.0
σ^{E} Electricity vs. primary energy inputs	0.3
σ^{COL} Coal vs. gas-oil	0.5
Substitution elasticities in final demand	
σ_{C} Fossil fuels vs. non-fossil fuels	0.8
σ_{FE} Fossil fuels vs. fossil fuels	0.3
Elasticities in international trade (Armington)	
σ^{D} Substitution elasticity between imports vs. domestic inputs	4.0
σ^{M} Substitution elasticity between imports vs. imports	8.0
σ^{tr} Transformation elasticity domestic vs. export	2.0
Exogenous supply elasticities of fossil fuels ε	
Crude oil	1.0
Coal	0.5
Natural gas	1.0

4. QUANTITATIVE ASSESSMENT OF CARBON ABATEMENT POLICIES

This section presents quantitative estimates for the economic impacts of carbon abatement restrictions under the Kyoto Protocol. Our main objective is to show how our static general equilibrium model of the global economy can be used to identify important determinants of adjustment costs across various regions. These determinants can be grouped into three categories. First, there are the policy settings such as the initial endowment with carbon emission rights or the degree of coordinated policies that characterize the design of any global abatement scenario. Second, there are assumptions underlying the basic model structure – most notably elasticities – which reflect the sensitivity of demand-side and supply-side responses to exogenous policy changes. Third, a larger part of the differences in the marginal and inframarginal costs of carbon emission constraints across regions may be traced back to structural differences in their economic and energy systems.

We will illustrate in the following how a shift in the policy design or changes in the model parametrization affect the model results. Although such a sensitivity analysis can clearly not be exhaustive, it is an indispensable step in any credible CGE analysis of policy interference, as it conveys important information on the robustness of results.

In our core simulations, we examine three different scenarios on the degree of international emissions trading:

[NOTRADE] Annex B countries can trade emission rights as allocated under the Kyoto Protocol only within domestic borders. There is no international trade in permit rights. This scenario is equivalent to a situation where Annex B countries apply domestic carbon taxes that are high enough to meet their individual Kyoto commitments.

[ANNEXB] All Annex B countries including FSU and CEA are allowed to trade emissions with each other.

[GLOBAL] There are no regional restrictions to emissions trading. Non-Annex B countries participate in global emissions trading with initial permit endowments which are equal to their Business-as-Usual emission level.

A fourth policy scenario accounts for the recent withdrawal of the USA as stated by President Bush in March 2001:

[NOUSA] The Kyoto Protocol is implemented without participation of the USA. All remaining countries meet their individual targets through strictly domestic action.

We then assess how changes in key model parameters affect our results. The objective is to strengthen the thinking of non-technical readers on major drivers of the model results. The first set of runs deals with the question about the extent transaction costs reduce the efficiency gains from ‘where’ – flexibility provided by the use of flexible instruments:

[TCOST] In the global trading scenario we have not incorporated any additional costs that might result from the setup and control (costs for monitoring, verification, certification, etc.) of flexible instruments. Many people believe that these costs can be substantial, particularly if some sort of emissions trading takes place between Annex B and non-Annex B countries. In the TCOST runs, we assess how the level of transaction costs affects the efficiency properties of the GLOBAL trading scenario. We assume that transaction costs apply to carbon exports from non-Annex B countries only, and will be incurred by them, also.

The next scenario examines the importance of the underlying baseline projections on economic growth and emissions under Business-as-Usual:

[BASELINE] As compared to the reference case, we adopt more optimistic assumptions on economic growth, which implies – *ceteris paribus* – higher demands for fossil fuels and higher BaU carbon emissions.

Finally, we assess the sensitivity of results with respect to changes in key assumptions underlying our core simulations: ease of substitution between domestic and imported goods (ARMINGTON), oil price responses (OIL), and the inefficiency of raising public funds (MCF):

[ARMINGTON] As described in Section 3, we represent trade in goods with an Armington structure. Imports are imperfect substitutes for domestically produced goods. The elasticity of substitution between imports and domestically produced goods, referred to as the Armington elasticity, measures how easily imports can substitute for domestic goods. In the scenario ARMINGTON, we vary the values of Armington elasticities to quantify the induced changes in the trade impacts of carbon abatement policies.

[OIL] The supply elasticity for oil determines how the world oil price responds to changes in world oil demand. We employ alternative values for the oil supply elasticity to investigate the economic implications on oil-exporting and oil-importing regions.

[MCF] The issue of revenue recycling has received lots of attention in the scientific and policy debate during the last decade. Environmental policies that raise public revenues can be complemented by revenue-neutral cuts of distortionary fiscal taxes. This provides prospects for the well-known double-dividend hypothesis from environmental taxation (see, for example, Pezzey 1992, Goulder 1995a). In our core simulations, we assume that revenues from carbon taxes or permit sales are recycled lump-sum to the representative agent in each region. In the scenario MCF we analyze how reductions in distortionary fiscal taxes will affect the gross costs of carbon abatement policies, i.e. the costs excluding environmental benefits.

All simulations are measured against the BaU scenario where no carbon emission restrictions apply. For the sake of brevity, we restrict sensitivity analyses to the NOTRADE policy setting in which emission targets are met through strictly domestic action. The NOTRADE reference setting is denoted as REF in Tables 3.12 to 3.39 below, summarizing the results of our sensitivity analysis.[10]

4.1 Effective Reduction Requirements

An important feature of any international agreement on greenhouse gas abatement is the extent to which it binds the involved economies in the future; the magnitude and distribution of costs associated with the implementation of future emission constraints depend on the Business-as-Usual (BaU) projections for gross domestic product, fuel prices, energy efficiency improvements etc. As outlined in Section 3, we infer the BaU structure of the model's regions for 2010 based on recent expert projections on economic development (DOE 1998). In our comparative static analysis, we measure the economic effects associated with abatement policies relative to the BaU in 2010.

It is important to notice that the nominal reduction targets to which Annex B countries have committed themselves under the Kyoto Protocol may substantially differ from the effective reduction requirements they face under BaU in 2010. Emissions of most Annex B countries have grown significantly along the baseline compared to 1990 levels. The Kyoto targets which are stated with respect to 1990 then translate into much higher effective carbon requirements with respect to BaU emission levels in 2010. Table 3.3 reports both the nominal Kyoto commitments as well as the effective reduction requirements across Annex B countries in 2010.

We see, for example, that the USA, which committed itself to a 7% reduction target with respect to 1990 levels, would have an effective cutback requirement of more than 30% as compared to the 2010 BaU level if it were to ratify the Protocol.[11]

Table 3.3 Nominal and effective CO_2 reduction requirements (in %)

Region	Nominal reduction (wrt 1990)	Effective reduction (wrt 2010)
CEA	7.00	–4.21
EUR	7.73	16.60
FSU	0.00	–31.74
JPN	6.00	23.05
OOE	0.91	22.68
USA	7.00	33.19

OOE is allowed to increase emissions under the Kyoto Protocol by 7% over 1990 levels, while it effectively faces the need for a decrease by more than 20% from BaU emissions in 2010. On the other hand, regions CEA and particularly FSU will stay below their 1990 emission levels due to major structural breaks between 1990 and 2000.

4.2 NOTRADE: Domestic Abatement Policies

4.2.1 Marginal abatement costs and welfare impacts

Table 3.4 reports the marginal abatement costs and welfare changes emerging from the implementation of the Kyoto targets through strictly domestic carbon abatement policies. In this framework, the marginal abatement costs are equivalent to the domestic carbon tax, which must be levied in order to achieve the exogenous emissions reduction target.

Obviously, the marginal abatement costs for non-Annex B countries are zero, because they have not committed themselves to any emission limitation. Among Annex B countries, the Kyoto targets do not become binding for CEA and FSU. All other Annex B parties, i.e. OECD countries, must cut back their BaU emissions substantially, which is reflected in the level of marginal abatement costs. Partial equilibrium analysis suggests that the level of abatement is a major determinant of the marginal abatement costs. The further out we are on the abatement cost curve, the more costly it is at the margin to replace carbon in production and consumption.

However, cross-country comparison of reduction requirements and marginal abatement costs in Table 3.4 reveals that the relative cutback requirements are only one determinant of marginal abatement costs. The latter depend also on the BaU energy price levels.

Table 3.4 Marginal abatement costs and welfare effects

Region	Marginal abatement cost*	Welfare effect**
CEA	-	0.29
EUR	112.76	–0.18
FSU	-	–0.25
JPN	229.36	–0.32
OOE	106.74	–0.66
USA	159.53	–0.60
ASI	-	0.03
CHN	-	0.22
IND	-	0.20
MPC	-	–0.48
ROW	-	–0.06

Notes: * $US95 per ton of carbon
** in % change of real consumption as compared to BaU

Typically, a country with higher BaU energy prices will require larger carbon taxes to achieve the same percentage emissions reduction than countries with lower BaU energy prices.[12] Differences in carbon intensities of sectors across countries play another important role in explaining the variation in marginal abatement costs. Countries which use carbon-intensive coal heavily in activities where fuel switching to less carbon-intensive oil or gas comes relatively cheap, face lower marginal abatement costs to meet the same reduction than countries which use relatively little carbon in sectors with low-cost substitution options.

These features explain, for example, why JPN faces much higher carbon taxes compared to USA, although its percentage reduction target is smaller: BaU energy prices in JPN are considerably higher than in USA. In addition, JPN has little scope for cheap inter-fuel substitution in electricity generation, which is largely nuclear-power based.

4.2.2 Welfare effects

The static welfare impacts are measured as the percentage change in real consumption with respect to BaU. Two things should be kept in mind when interpreting these numbers: First, we report only the gross economic impact of carbon emission constraints without accounting for environmental benefits.

Therefore, losses in real consumption cannot be construed as an argument against environmental action in cost-benefit terms. Second, in our core simulations, we do not incorporate second-best considerations which might raise the scope for a double dividend from environmental taxation.[13] Under these conditions, the implications of emission constraints on the global economy are straightforward. At the global level, adjustment of production and consumption patterns towards less carbon intensity implies a less productive use of resources, which translates into a decline of real income, i.e. less consumption, given fixed investment. At the single-country level, however, the welfare implications are ambiguous. Carbon abatement in large open economies not only causes adjustment of domestic production and consumption patterns, but also influences international prices via changes in exports and imports. Changes in international prices (terms-of-trade impacts) imply a secondary benefit or burden which may alter the economic implications of the primary domestic abatement policy. Some countries may shift part of their domestic abatement costs to trading partners, while other abating countries face additional welfare losses from a deterioration of their terms of trade. These international spillovers also explain why countries which do not face any emission restriction under the Kyoto Protocol may nevertheless be significantly affected by the abatement of Annex B countries.[14]

Table 3.4 suggests that for OECD countries, the unambiguous primary domestic policy effect is not dominated by secondary terms-of-trade effects, which is not surprising given the stringency of the respective emission constraints. For countries that do not face a binding emission constraint, the secondary terms-of-trade effect is equal to the total welfare effect as reported in Table 3.4. Given our core model parametrization, we see that spillover effects harm FSU, MPC and ROW, whereas they are beneficial to developing regions ASI, CHN and IND, as well as the economies in transition CEA.

Among international spillovers that result from trade in goods, most important are the adjustments on international energy markets. The cut-back in demands for fossil fuels from abating OECD countries depresses the international energy prices. Lower world energy prices harm energy exporting countries and benefit energy importing countries. In this vein, spillover effects from energy markets cause welfare losses for fuel exporters FSU, MPC and ROW, because the prices of energy exports decline and, therefore, export revenues fall. CEA as well as developing regions ASI, CHN and IND are net importers of fuels and therefore benefit from the depression of world energy prices.

The welfare implications of international price changes in non-energy markets, where traded goods are differentiated by region of origin, are more complex. Higher energy costs raise prices of non-energy goods produced in Annex B countries. Countries that import these goods suffer from higher prices to the extent that they cannot easily move away from more expensive imports towards cheaper imports from non-abating countries. The implicit burden shifting of carbon taxes on non-energy markets not only applies between abating and non-abating countries but also within the group of abating Annex B regions; for example, OOE, which has relatively low marginal abatement costs, suffers from the increased export prices of trading partners with high marginal abatement costs, such as Japan.

Due to reduced economic activity (productivity) in abating developed regions, trading partners face a negative scale or income effect as the import demand by the industrialized world declines, which exerts a downward pressure on the prices of demanded goods. On the other hand, this effect may be (partially) offset by an opposite substitution effect. Developing countries may gain market shares because their exports become more competitive. As reported in Table 3.4, all non-Annex B countries, apart from MPC and ROW, improve their terms of trade. It should be noted that this result is rather sensitive to the representation of price responses on the world crude oil and coal market. When larger cuts in oil and coal demand cause only a small decrease in world fuel prices, the positive spillover for oil and coal importing developing countries is significantly reduced and may be offset by negative spillovers on other (non-energy) markets.

Moreover, our choice of a comparative-static framework potentially overstates the gains from unilateral action by Annex B countries for developing countries. We do not account for the effects of reduced investment on the economic growth and import demand of industrialized countries. As complementary analysis in a dynamic framework shows (see, for example, Böhringer and Rutherford 2001), the additional income losses for developing countries may then have the effect that most of them lose on balance from trade distortions caused by emission constraints in the industrialized countries.

4.2.3 Comparative advantage and the pattern of trade

In the conventional economic paradigm, comparative advantage refers to the relative cost of producing goods in a particular country in comparison to the relative cost of producing the same goods elsewhere. Unilateral action has important implications for comparative advantage, i.e. the competitiveness of industrial sectors across regions. Carbon emission constraints increase the cost of production, particularly for those sectors in which energy represents a significant share of direct and indirect costs. At the sectoral level, policy makers in Annex B countries are, therefore, concerned about the negative repercussions of emission constraints on production and employment in energy-intensive sectors. Tables 3.5 and 3.7 indicate why.[15]

Due to unilateral abatement, energy-intensive sectors in Annex B countries, which face binding emissions constraints, lose competitiveness. Most affected is energy-intensive production in the USA, which experiences the highest increase among Annex B countries, given the low US energy costs under BaU. CEA and FSU, as well as all developing non-Annex B countries, face a cost advantage because they do not have to levy domestic carbon taxes.

Even though energy costs do not constitute a large share of value-added in energy-intensive production, the cost increase in OECD countries changes comparative advantage sufficiently to induce large changes in trade flows. As we can see from Table 3.7, the EU exports to FSU drop by nearly 10%, whereas imports from FSU to EU increase by roughly 9%.

Table 3.5 Impacts on energy-intensive production (% change)

Region	
CEA	1.93
EUR	–0.53
FSU	4.87
JPN	–0.82
OOE	–1.33
USA	–2.33
ASI	1.47
CHN	2.08
IND	2.24
MPC	3.50
ROW	1.17

4.2.4 Environmental Effectiveness and Leakage

Given the global nature of the carbon externality, sub-global abatement action induces efficiency losses due to carbon leakage. Under the Kyoto Protocol, emissions reduction in Annex B countries can be offset by increased emissions elsewhere through the relocation of energy-intensive production or depressed prices of fossil fuels. This effect is measured by the leakage rate, which – in general terms – is defined as the ratio of the emissions increase in non-abating countries to the total emissions reduction in abating countries. If leakage is significant, the design of unilateral abatement policies may be altered to avoid leakage and increase the efficiency of sub-global abatement strategies. One approach would be to lower the abatement burden on emission-intensive industries via (partial) exemptions or grandfathered permits (see, for example, Böhringer 1998a, Böhringer, Ferris and Rutherford 1998, Böhringer, Rutherford and Voss 1998).

Table 3.6 summarizes the leakage rates at the regional and global level for the NOTRADE scenario. In total, the emissions reduction of Annex B countries are offset by more than 20% through emission increases by non-Annex B countries, with CHN as the main source for leakage.

The magnitude of the leakage rate can be traced back to our treatment of fossil energy markets. We assume that oil and coal markets are homogeneous due to relatively low transport costs. A drop in oil and coal demand by Annex B countries then reduces world prices for coal and oil more than if we had assumed heterogeneity of these goods. This induces a larger increase of oil and coal consumption in non-Annex B countries.

There are several other factors that determine the leakage rate and, hence, the effectiveness of sub-global abatement policies. Among these are the assumed degree of the scope of international carbon trading (see Section 4.3) or the substitutability between imported and domestic production (see Section 4.7).

4.3 ANNEX B and GLOBAL: The Impacts of Emissions Trading

One major controversial issue of the Kyoto Protocol is the extent to which emissions reduction commitments by individual countries can be met through the use of flexible instruments such as emissions trading. In principle, the Kyoto Protocol allows emissions trading across signatory countries; however the rules are vague, and have yet to be defined.[16] With respect to the scope of tradable permits, the Kyoto Protocol states that any trading shall be ‘supplemental’ to domestic action for the purpose of meeting obligations. The principle of supplementarity was inserted mainly due to concerns in the EU about hot air.

Table 3.6 Leakage rates (in %)

Region	Leakage rate
ASI	0.97
CHN	14.15
IND	2.40
MPC	1.55
ROW	2.82
TOTAL	21.90

This increases the effective emissions compared to strictly domestic action because regions with BaU emissions below target levels can trade in their abundant emission rights. This will be particularly relevant for FSU, where projected emissions are far below the Kyoto entitlements.

Estimates of hot air range up to 500–650 million tons of CO_2, which corresponds to 70–90% of the total Annex B reduction commitment (Herold 1998, Böhringer 2000).

First of all, we see that Annex B emissions trading substantially reduces the negative impacts of meeting Kyoto targets for the global economy. Compliance costs are reduced to roughly a third of the cost figure in the NOTRADE reference case. Note that global welfare gains stem from two different sources. First, there are gains from the equalization of marginal abatement costs across Annex B countries. Second, there are gains from an implicit relaxation of the NOTRADE emission constraints due to hot air. In fact, CEA and, in particular, FSU, sell larger amounts of formerly abundant emission rights.

Even more disputed than emissions trading within the block of Annex B countries is the implicit extension of emissions trading to non-Annex B countries via the Clean Development Mechanism. While this has a clear economic efficiency rationale, opponents of global emissions trading systems such as the EU refer to potential loopholes associated with the problems of defining credible emission baselines and the lack of regulations regarding monitoring or verification.

In this context, estimates of the magnitude of efficiency gains from trade provide a useful reference point against which one can count transaction costs for the institutional set-up and control of emissions trading (see Section 4.5).

Table 3.7 Trade in energy-intensive production (% change)

Imports from Row region to Column region

	CEA	EUR	FSU	JPN	OOE	USA	ASI	CHN	IND	MPC	ROW
CEA	1.51	3.59	–5.69	6.34	5.96	8.67	1.58	–0.22	–1.96	0.75	0.67
EUR	–2.36	–0.36	–9.88	2.29	1.91	4.56	–2.28	–4.03	–5.62	–3.08	–3.14
FSU	6.77	8.89	–1.14	11.81	11.31	14.19	6.72	4.86	3.33	5.88	5.80
JPN	–3.54	–1.59	–11.04	0.82	0.58	3.17	–3.45	–5.12	–6.66	–4.27	–4.39
OOE	–6.11	–4.29	–13.57	–1.69	–1.99	0.37	–6.10	–7.71	–9.28	–6.86	–6.93
USA	–5.69	–3.79	–13.15	–1.23	–1.71	–2.33	–5.59	–7.23	–8.64	–6.44	–6.39
ASI	1.24	3.35	–6.38	6.11	5.67	8.42	1.32	–0.44	–2.08	0.53	0.43
CHN	2.31	4.37	–5.42	7.13	6.71	9.46	2.34	0.54	–1.11	1.53	1.44
IND	3.38	5.45	–4.38	8.23	7.82	10.61	3.39	1.59	2.24	2.58	2.50
MPC	2.45	4.52	–5.29	7.27	6.83	9.59	2.47	0.66	–1.02	1.64	1.59
ROW	0.85	2.90	–6.83	5.57	5.25	7.97	0.86	–0.92	–2.49	0.08	0.01

Tables 3.8 and 3.9 summarize the changes in marginal and inframarginal abatement costs when we move from NOTRADE to policies which allow for trade in permits among Annex B countries (ANNEXB) or all world regions (GLOBAL).

Table 3.8 Marginal abatement costs (in $US95 per ton of carbon)

Region	NOTRADE	ANNEXB	GLOBAL
CEA	-	57	31
EUR	113	57	31
FSU	-	57	31
JPN	229	57	31
OOE	107	57	31
USA	160	57	31
ASI	-	-	31
CHN	-	-	31
IND	-	-	31
MPC	-	-	31
ROW	-	-	31

Table 3.9 Welfare impacts (in % change of real consumption)

REGION	NOTRADE	ANNEXB	GLOBAL
CEA	0.29	0.87	0.37
EUR	–0.18	–0.11	–0.03
FSU	–0.25	5.16	2.58
JPN	–0.32	–0.09	–0.01
OOE	–0.66	–0.53	–0.46
USA	–0.60	–0.38	–0.24
ASI	0.03	0.03	0.08
CHN	0.22	0.15	0.25
IND	0.20	0.15	0.03
MPC	–0.48	–0.38	–0.44
ROW	–0.06	–0.05	–0.09
TOTAL	–0.29	–0.09	–0.06

The pattern of permit trade is determined by the level of marginal abatement costs under NOTRADE compared to the equalized marginal abatement costs for tradable permits. Countries whose marginal abatement costs under NOTRADE are below the uniform permit price will sell permits and abate more emissions. In turn, countries whose marginal abatement costs are above the uniform permit price rate will buy permits and abate fewer emissions.

Table 3.10 Leakage rates (in %)

Region	NOTRADE	ANNEXB
ASI	0.97	0.71
CHN	14.15	9.85
IND	2.40	1.70
MPC	1.55	1.15
ROW	2.82	2.39
TOTAL	21.90	15.79

Table 3.11 Carbon emissions (in Gt)

Region	BASELINE	NOTRADE	ANNEXB	GLOBAL
CEA	0.25	0.26	0.20	0.23
EUR	1.16	1.01	1.10	1.16
FSU	0.82	0.94	0.70	0.77
JPN	0.45	0.34	0.41	0.43
OOE	0.27	0.22	0.24	0.26
USA	2.07	1.41	1.75	1.92
ASI	0.36	0.37	0.37	0.34
CHN	1.35	1.62	1.57	1.24
IND	0.32	0.36	0.35	0.30
MPC	0.62	0.65	0.65	0.59
ROW	0.66	0.70	0.69	0.63
TOTAL	8.33	7.88	8.03	7.87

All Annex B countries benefit substantially from Annex B trade in permits.[17] There are huge monetary transfers from emission sales to FSU, which turns the region's welfare loss under NOTRADE into huge welfare gains as compared to BaU. CEA further improves welfare beyond BaU levels through the sales of emissions. OECD countries face much smaller marginal abatement costs due to additional supplies of emission rights from FSU and CEA. The drop in marginal abatement costs is reflected in the decrease of inframarginal consumption losses. International spillovers to non-Annex B countries are reduced for Annex B trading as the changes in comparative advantage, i.e. the terms of trade, become less pronounced.

As expected, global emissions trading further reduces the world-wide costs of Kyoto. However, the implied cost reduction associated with a shift from ANNEXB to GLOBAL is much smaller than that generated by the move from NOTRADE to ANNEXB (see also the respective changes in marginal abatement costs). Hot air from CEA and FSU obviously accounts for a larger share of welfare gains achievable through permit trading. Among Annex B countries, only the OECD regions benefit from global emissions trading as compared to the ANNEXB scenario. The reason for this is obvious: global trading increases the supply of emission abatement from abroad, which further relaxes the Kyoto emission constraint on OECD countries and decreases the price of tradable emission permits. On the other hand, both FSU and CEA suffer from the decline in the permit price, which implies a substantial loss of their income from permit sales.

The leakage rate under ANNEXB drops by a fourth compared to the NOTRADE case. Emissions trading reduces the cost increase for energy-intensive sectors in OECD countries, which diminishes counterproductive relocation of ‘dirty’ industries to non-abating countries. Nevertheless, global emissions rise under ANNEXB trading compared to the NOTRADE scenario: the decline in leakage gets more than offset by hot air from FSU and CEA. In the GLOBAL trading scenario, leakage becomes zero by definition. Global carbon emissions are at the same level as under NOTRADE. This indicates that, under GLOBAL, avoided leakage is just offset by hot air.

4.4 NOUSA: Kyoto without USA

In March 2001, the USA under President Bush switched its attitude towards the Kyoto Protocol and declared ‘We have no interest in implementing this treaty’. Since then, other major Annex B countries have emphasized their willingness to implement Kyoto even without US participation. The scenario NOUSA reflects this policy situation in assuming that the USA does not face any emission constraint on its economy, whereas all other ANNEXB countries meet their Kyoto commitments through domestic action. Tables 3.12 through 3.15 summarize the economic and environmental implications of this scenario.

Without emission constraint, the US economy is more or less unaffected by the carbon abatement policies of the other Annex B regions. However, the higher fossil fuel demand by the US economy has important implications for spillovers from international energy markets. Prices for coal and oil do not fall as much, which is beneficial for energy exporting regions MPC and ROW, but harmful to energy importers such as EUR, JPN or developing regions CHN, IND and ASI. Non-compliance of the USA results in significantly higher global carbon emissions than in the reference case. The USA becomes more competitive in the production of energy-intensive goods. This increases the global carbon leakage up to 28%, with CHN and USA accounting for the largest part of it.

Table 3.12 Welfare impacts (in % change of real consumption)

Region	REF	NOUSA
CEA	0.29	0.16
EUR	–0.18	–0.22
FSU	–0.25	–0.46
JPN	–0.32	–0.36
OOE	–0.66	–0.44
USA	–0.60	0.01
ASI	0.03	–0.02
CHN	0.22	0.03
IND	0.20	0.04
MPC	–0.48	–0.15
ROW	–0.06	–0.03
TOTAL	–0.29	–0.14

4.5 TCOST: The Effects of Transaction Costs

A common assumption of CGE models is that all decisions are made under certainty. In the case of climate change this is doubtful.

If a country or company uses one of the flexible instruments to achieve its reduction target, it must be certain that purchased emission rights will be valid.Otherwise, it will bear the risk of non-compliance and corresponding sanctions. Incorporating this uncertainty into the modeling framework might change the optimal choice between domestic and foreign actions, since reduction measures abroad might bear higher risks, shifting the relative advantage to domestic actions.

Closely linked to the risk problem is the issue of transaction costs. To reduce or avoid risks, the purchasing party might insure the projects or diversify through carbon funds. Further options would be more stringent rules for project verification and certification. All these strategies are associated with higher transactions costs. Model simulations that neglect the existence of transaction costs overestimate the potential benefit from the international trade of emission permits.

Table 3.13 Marginal abatement costs (in $US95 per ton of carbon)

Region	REF	NOUSA
CEA	-	-
EUR	113	107
FSU	-	-
JPN	229	224
OOE	107	98
USA	160	-
ASI	-	-
CHN	-	-
IND	-	-
MPC	-	-
ROW	-	-

Table 3.14 Leakage rates (in %)

Region	REF	NOUSA
USA	0.00	10.28
ASI	0.97	0.88
CHN	14.15	10.77
IND	2.40	1.83
MPC	1.55	1.54
ROW	2.82	2.83
TOTAL	21.90	28.13

These considerations show the need to assess the effects of transaction costs. In the scenario GLOBAL, we assume that the transaction costs for transferring abatement from non-Annex B countries to Annex B countries equal zero. We now impose transaction costs of $US5 (CDM05), $US10

(CDM10) or \$US20 (CDM20) on every ton of carbon that is sold from non-Annex B countries to Annex B countries. Transaction costs are represented as resource use which does not generate revenues for the partners involved in emissions trading. In the model, we incorporate transaction costs as a requirement for human resources (i.e. labor) to monitor and verify trade in emission abatement.[18]

3.15 Carbon emissions (in Gt)

Region	REF	NOUSA
CEA	0.26	0.26
EUR	1.01	1.01
FSU	0.94	0.90
JPN	0.34	0.34
OOE	0.22	0.22
USA	1.41	2.14
ASI	0.37	0.37
CHN	1.62	1.51
IND	0.36	0.34
MPC	0.65	0.64
ROW	0.70	0.68
TOTAL	7.88	8.41

Tables 3.16–3.18 report the economic implications of transaction costs. Not surprisingly, they reduce the magnitude of efficiency gains from emissions trading with non-Annex B countries. The higher the transaction costs are, the higher the global effective permit prices are (as indicated by the marginal abatement costs of Annex B countries) and the lower the overall level of permit trading. The payment received by non-Annex B countries for any ton of carbon abated domestically equals the difference between the global permit price Annex B countries perceive and the assumed transaction costs. Transaction costs that apply to emissions trading with non-Annex B countries but not to emission sales from Annex B countries are beneficial to CEA and FSU. These countries can now sell their permits at higher prices than in the GLOBAL scenario without any transaction costs. Due to this implied ‘mark-up’ for FSU and CEA, OECD countries do worse than under the scenario GLOBAL because they move to higher marginal abatement costs. Except for CHN, the largest non-Annex B supplier of emission permits

in absolute terms, transaction costs hardly affect welfare for the other non-Annex B countries simply because their level of trade is already rather small under GLOBAL without any transaction cost.[19]

3.16 Welfare impact (in % change of real consumption)

Region	GLOBAL	CDM05	CDM10	CDM20
CEA	0.37	0.40	0.44	0.53
EUR	–0.03	–0.04	–0.05	–0.06
FSU	2.58	2.80	3.02	3.52
JPN	–0.01	–0.01	–0.02	–0.03
OOE	–0.46	–0.47	–0.48	–0.51
USA	–0.24	–0.25	–0.27	–0.30
ASI	0.08	0.07	0.07	0.06
CHN	0.25	0.22	0.20	0.16
IND	0.03	0.02	0.02	0.02
MPC	–0.44	–0.44	–0.45	–0.45
ROW	–0.09	–0.09	–0.09	–0.09
TOTAL	–0.06	–0.07	–0.07	–0.08

Table 3.17 Marginal abatement costs (in $US95 per ton of carbon)

Region	GLOBAL	CDM05	CDM10	CDM20
CEA	31	33	36	41
EUR	31	33	36	41
FSU	31	33	36	41
JPN	31	33	36	41
OOE	31	33	36	41
USA	31	33	36	41
ASI	31	28	26	21
CHN	31	28	26	21
IND	31	28	26	21
MPC	31	28	26	21
ROW	31	28	26	21

4.6 BASELINE: Higher Growth Projections

The cost estimates for carbon abatement depend crucially on BaU projections for gross domestic production, energy efficiency improvements, fuel prices etc. High economic growth, for example, increases the effective abatement requirement; and because the Kyoto commitments refer to 1990 emissions levels, this will imply higher total abatement costs.

Table 3.18 Carbon emissions (in Gt)

Region	GLOBAL	CDM05	CDM10	CDM20
CEA	0.23	0.22	0.22	0.22
EUR	1.16	1.15	1.14	1.13
FSU	0.77	0.77	0.76	0.74
JPN	0.43	0.42	0.42	0.42
OOE	0.26	0.26	0.26	0.26
USA	1.92	1.91	1.89	1.85
ASI	0.34	0.34	0.34	0.35
CHN	1.24	1.26	1.28	1.33
IND	0.30	0.31	0.31	0.32
MPC	0.59	0.59	0.60	0.61
ROW	0.63	0.63	0.64	0.65
TOTAL	7.87	7.87	7.87	7.87

Table 3.19 Effective CO_2 emission cut-back requirements under BASELINE (in % with respect to 2010)

Region	REF	BASELINE
CEA	–4.21	1.19
EUR	16.60	21.03
FSU	–31.74	–28.78
JPN	23.05	27.33
OOE	22.68	26.40
USA	33.19	33.48

Our sensitivity analysis below illustrates the importance of baseline assumptions, which generally receive little attention in the literature.[20] Based on projections by the DOE for alternative economic growth paths (DOE 1998), we adopt higher GDP growth rates that are linked to higher demands in fossil fuels as compared to our reference case. In the higher growth scenario, Table 3.19 reports the increase in the effective cut-back requirements of Annex B countries as compared to the reference case.

Table 3.20 Welfare impacts (in % change of real consumption)

Region	REF	HI
CEA	0.29	0.48
EUR	–0.18	–0.46
FSU	–0.25	–0.53
JPN	–0.32	–0.63
OOE	–0.66	–1.09
USA	–0.60	–0.76
ASI	0.03	0.08
CHN	0.22	0.31
IND	0.20	0.32
MPC	–0.48	–0.77
ROW	–0.06	–0.11
TOTAL	–0.29	–0.49

Table 3.21 Marginal abatement costs (in $US95 per ton of carbon)

Region	REF	HI
CEA	-	14
EUR	113	204
FSU	-	-
JPN	229	379
OOE	107	167
USA	160	207
ASI	-	-
CHN	-	-
IND	-	-
MPC	-	-
ROW	-	-

The increase in projected BaU emissions and effective cutback requirements causes a steep rise in marginal and inframarginal abatement costs (Tables 3.20 and 3.21).

International spillovers to non-abating countries from abatement policies in Annex B countries are substantially magnified. As expected, higher effective reduction requirements in Annex B countries lead to larger changes in comparative advantage for energy-intensive industries (Table 3.22) and a higher leakage rate of sub-global action as compared to the reference case (Table 3.23).

Table 3.22 Energy-intensive production (% change)

Region	REF	HI
CEA	1.93	2.07
EUR	–0.53	–1.22
FSU	4.87	6.95
JPN	–0.82	–1.37
OOE	–1.33	–2.89
USA	–2.33	–3.03
ASI	1.47	2.41
CHN	2.08	3.05
IND	2.24	3.21
MPC	3.50	6.22
ROW	1.17	1.98

Table 3.23 Leakage rates (in %)

Region	REF	HI
ASI	0.97	1.31
CHN	14.15	17.40
IND	2.40	2.76
MPC	1.55	2.35
ROW	2.82	3.48
TOTAL	21.90	27.29

Table 3.24 Carbon emissions (in Gt)

Region	REF	HI
CEA	0.26	0.27
EUR	1.01	1.01
FSU	0.94	0.97
JPN	0.34	0.34
OOE	0.22	0.22
USA	1.41	1.41
ASI	0.37	0.45
CHN	1.62	2.02
IND	0.36	0.42
MPC	0.65	0.76
ROW	0.70	0.84
TOTAL	7.88	8.70

4.7 ARMINGTON: Low-and High-Trade Impact Cases

Apart from crude oil and coal, which are represented as homogeneous goods across regions, imported and domestically produced varieties of the same good are treated as imperfect substitutes. The trade-off between the two varieties is captured by the Armington elasticity. In our policy simulations, this trade elasticity affects, for example, the extent to which OECD's domestically produced goods are displaced by non-OECD imports when a carbon abatement policy raises the cost of OECD production. In the reference case, the elasticity of substitution between the domestic good and the import aggregate is set to 4, and the elasticity of imports from different regions within the import aggregate is set to 8. In the sensitivity analysis, we either halve (LOARM) or double (HIARM) these values.

From the perspective of a small open economy that faces fixed world market prices, the cost of its carbon abatement policy moves inversely with trade elasticities. When domestic and imported goods are closer substitutes, countries can more easily move away from carbon-intensive inputs into production and consumption (see Table 3.26). This primary effect of changes in the trade elasticities must be combined with secondary terms-of-trade effects. At the global level, terms-of-trade effects cancel out such that the welfare impact of higher trade elasticities is unambiguous: the welfare costs of emission constraints on the global economy decline (see Table 3.25). At the single-country level, the terms-of-trade effects may strengthen, weaken or even outweigh the unambiguous primary welfare effect associated with a change in trade elasticities.

3.25 Welfare impacts (in % change of real consumption)

Region	LOARM	REF	HIARM
CEA	0.30	0.29	0.30
EUR	–0.18	–0.18	–0.18
FSU	–0.42	–0.25	–0.15
JPN	–0.32	–0.32	–0.33
OOE	–0.75	–0.66	–0.63
USA	–0.56	–0.60	–0.62
ASI	0.03	0.03	0.02
CHN	0.16	0.22	0.26
IND	0.19	0.20	0.20
MPC	–0.68	–0.48	–0.40
ROW	–0.09	–0.06	–0.05
TOTAL	–0.30	–0.29	–0.29

3.26 Marginal abatement costs (in $US95 per ton of carbon)

Region	LOARM	REF	HIARM
CEA	-	-	-
EUR	121	113	108
FSU	-	-	-
JPN	255	229	216
OOE	114	107	102
USA	161	160	158
ASI	-	-	-
CHN	-	-	-
IND	-	-	-
MPC	-	-	-
ROW	-	-	-

In general, lower trade elasticities imply that cost advantages of countries with low or zero abatement costs translate into smaller gains in market shares. In other words, the trade elasticity determines the extent to which domestic abatement costs can be passed further to trading partners ('beggar-thy-neighbor'). With lower elasticities, a country importing carbon-intensive goods from a trading partner with high domestic abatement costs is less able to change from the expensive imports to cheaper domestically produced goods. As expected, higher trade elasticities enforce the adverse impacts on energy-intensive industries in abating OECD countries (Table 3.27) which causes an increase in the global leakage rate (Table 3.28).

3.27 Energy-intensive production (% change)

Region	LOARM	REF	HIARM
CEA	1.12	1.93	3.35
EUR	–0.47	–0.53	–0.66
FSU	4.21	4.87	5.90
JPN	–0.75	–0.82	–1.01
OOE	–0.67	–1.33	–2.57
USA	–1.88	–2.33	–3.11
ASI	0.85	1.47	2.66
CHN	1.52	2.08	3.15
IND	1.64	2.24	3.34
MPC	2.84	3.50	4.69
ROW	0.89	1.17	1.75

3.28 Leakage rates (in %)

Region	LOARM	REF	HIARM
ASI	0.94	0.97	1.05
CHN	13.69	14.15	14.72
IND	2.31	2.40	2.51
MPC	1.42	1.55	1.70
ROW	2.85	2.82	2.88
TOTAL	21.21	21.90	22.85

3.29 Carbon emissions (in Gt)

Region	LOARM	REF	HIARM
CEA	0.26	0.26	0.26
EUR	1.01	1.01	1.01
FSU	0.95	0.94	0.93
JPN	0.34	0.34	0.34
OOE	0.22	0.22	0.22
USA	1.41	1.41	1.41
ASI	0.37	0.37	0.37
CHN	1.59	1.62	1.64
IND	0.36	0.36	0.36
MPC	0.64	0.65	0.66
ROW	0.69	0.70	0.70
TOTAL	7.84	7.88	7.91

4.8 OIL: Responsiveness of crude oil prices

In the reference case, the crude oil supply elasticity is set to 1. In our sensitivity analysis, we double this value for the high elasticity case (HI_OIL) and halve it for the low elasticity case (LO_OIL).

3.30 Welfare impacts (in % change of real consumption)

Region	LO_OIL	REF	HI_OIL
CEA	0.38	0.29	0.23
EUR	–0.15	–0.18	–0.21
FSU	–0.26	–0.25	–0.23
JPN	–0.31	–0.32	–0.34
OOE	–0.66	–0.66	–0.66
USA	–0.58	–0.60	–0.62
ASI	0.08	0.03	0.01
CHN	0.25	0.22	0.21
IND	0.27	0.20	0.15
MPC	–0.69	–0.48	–0.33
ROW	–0.06	–0.06	–0.06
TOTAL	–0.28	–0.29	–0.30

Lower elasticities imply that the crude oil price is more responsive to a change in demand. Therefore, when the OECD reduces its demand for crude oil, the price drops more for lower elasticity values than for higher values. Increasing the price response causes oil exporting nations to suffer more when a carbon abatement policy is enacted.

3.31 Marginal abatement costs (in $US95 per ton of carbon)

Region	LO_OIL	REF	HI_OIL
CEA	-	-	-
EUR	114	113	112
FSU	-	-	-
JPN	231	229	228
OOE	108	107	106
USA	161	160	159
ASI	-	-	-
CHN	-	-	-
IND	-	-	-
MPC	-	-	-
ROW	-	-	-

3.32 Energy-intensive production (% change)

Region	LO_OIL	REF	HI_OIL
CEA	2.00	1.93	1.88
EUR	–0.53	–0.53	–0.53
FSU	4.93	4.87	4.82
JPN	–0.83	–0.82	–0.81
OOE	–1.31	–1.33	–1.37
USA	–2.35	–2.33	–2.32
ASI	1.47	1.47	1.47
CHN	2.09	2.08	2.08
IND	2.26	2.24	2.23
MPC	3.67	3.50	3.38
ROW	1.16	1.17	1.19

Conversely, higher price responses lead to greater benefits for oil-importing countries. This explains why oil-importing OECD countries and developing countries do worse for higher oil supply elasticities. The opposite applies to oil-exporting regions such as FSU and MPC.[21] As expected, leakage through adjustments in international oil markets declines with higher oil supply elasticities. However, the induced changes are rather small.

3.33 Leakage rates (in %)

Region	LO_OIL	REF	HI_OIL
ASI	1.09	0.97	0.89
CHN	14.21	14.15	14.12
IND	2.48	2.40	2.35
MPC	1.79	1.55	1.40
ROW	2.94	2.82	2.74
TOTAL	22.50	21.90	21.50

3.34 Carbon emissions (in Gt)

Region	LO_OIL	REF	HI_OIL
CEA	0.26	0.26	0.26
EUR	1.01	1.01	1.01
FSU	0.94	0.94	0.94
JPN	0.34	0.34	0.34
OOE	0.22	0.22	0.22
USA	1.41	1.41	1.41
ASI	0.37	0.37	0.37
CHN	1.62	1.62	1.62
IND	0.36	0.36	0.36
MPC	0.65	0.65	0.65
ROW	0.70	0.70	0.70
TOTAL	7.89	7.88	7.87

4.9 MCF: The Gains from Revenue Recycling

In our core simulations, the revenues of carbon taxes are recycled lump-sum to the representative agent in each region. We do not capture therefore the welfare effects of swapping carbon taxes for distortionary existing taxes. In our global model of the world economy, we are not able to represent country-specific tax distortions, due to the level of aggregation and the lack of appropriate data.

3.35 Welfare impacts (in % change of real consumption)

Region	REF	MCF05	MCF10	MCF25
CEA	0.29	0.29	0.30	0.30
EUR	–0.18	–0.12	–0.06	0.12
FSU	–0.25	–0.24	–0.24	–0.24
JPN	–0.32	–0.25	–0.17	0.07
OOE	–0.66	–0.55	–0.43	–0.07
USA	–0.60	–0.46	–0.32	0.10
ASI	0.03	0.04	0.04	0.05
CHN	0.22	0.23	0.23	0.24
IND	0.20	0.20	0.20	0.20
MPC	–0.48	–0.47	–0.47	–0.45
ROW	–0.06	–0.06	–0.05	–0.05
TOTAL	–0.29	–0.22	–0.15	0.06

3.36 Marginal abatement costs (in $US95 per ton of carbon)

Region	REF	MCF05	MCF10	MCF25
CEA	-	-	-	-
EUR	113	113	113	115
FSU	-	-	-	-
JPN	229	230	231	233
OOE	107	107	108	109
USA	160	160	161	163
ASI	-	-	-	-
CHN	-	-	-	-
IND	-	-	-	-
MPC	-	-	-	-
ROW	-	-	-	-

Therefore, we can address the issue of revenue recycling only in a very stylized way. We adopt uniform estimates for the marginal costs of public funds (MCF) (see Böhringer, Ruocco and Wiegard 2001a, 2001b) across regions and calculate to what extent revenues from carbon taxes in abating countries reduce the welfare costs of carbon emission constraints. As a simple shortcut, we multiply the carbon tax revenue with the MCF and place the resulting amount to the credit of the representative agent in the respective region.

We study the implications of revenue recycling for cases where MCFs in Annex B countries equal 0% (the reference case), 10% and 25%. Not surprisingly, we find that our stylized representation of MCFs dramatically reduces the costs for abating OECD countries. For an MCF of 25%, domestic carbon tax policies may even yield net welfare gains.

The latter result should be treated with some caution, because we exclude the welfare-reducing tax interaction effects of existing distortionary taxes with carbon taxes (see Goulder 1995b). Non-abating countries are hardly affected by the recycling policies; neither is global environmental effectiveness.

3.37 Energy-intensive production (% change)

Region	REF	MCF05	MCF10	MCF25
CEA	1.93	1.93	1.93	1.93
EUR	–0.53	–0.48	–0.43	–0.27
FSU	4.87	4.87	4.88	4.90
JPN	–0.82	–0.77	–0.72	–0.56
OOE	–1.33	–1.25	–1.16	–0.89
USA	–2.33	–2.23	–2.13	–1.83
ASI	1.47	1.47	1.47	1.48
CHN	2.08	2.08	2.08	2.09
IND	2.24	2.24	2.24	2.25
MPC	3.50	3.49	3.48	3.46
ROW	1.17	1.17	1.17	1.17

3.38 Leakage rates (in %)

Region	REF	MCF05	MCF10	MCF25
ASI	0.97	0.97	0.97	0.97
CHN	14.15	14.17	14.19	14.24
IND	2.40	2.41	2.41	2.41
MPC	1.55	1.55	1.55	1.54
ROW	2.82	2.82	2.82	2.81
TOTAL	21.90	21.92	21.93	21.97

3.39 Carbon emissions (in Gt)

Region	REF	MCF05	MCF10	MCF25
CEA	0.26	0.26	0.26	0.26
EUR	1.01	1.01	1.01	1.01
FSU	0.94	0.94	0.94	0.94
JPN	0.34	0.34	0.34	0.34
OOE	0.22	0.22	0.22	0.22
USA	1.41	1.41	1.41	1.41
ASI	0.37	0.37	0.37	0.37
CHN	1.62	1.62	1.62	1.62
IND	0.36	0.36	0.36	0.36
MPC	0.65	0.65	0.65	0.65
ROW	0.70	0.70	0.70	0.70
TOTAL	7.88	7.88	7.88	7.88

5. CONCLUDING REMARKS

There are two fundamental issues whose reconciliation is crucial for any international agreement on greenhouse gas emission abatement strategies: efficiency in terms of overall abatement costs, and equity in terms of a ‘fair’ distribution of these costs across countries. Consequently, the climate policy debate requires quantitative estimates of the magnitude and regional distribution of costs that are associated with alternative policy strategies to reach some given emissions reduction targets. In this context, analytical models of economic adjustment to emission constraints provide an important tool for gaining policy-relevant insights since they accommodate the systematic and consistent assessment of how changes in the policy design or structural assumptions may affect simulation results and policy conclusions.

It is sometimes asserted that quantitative economic models do not provide useful information because they produce different results. This is a false perception of the role of economic modeling: differences in results do not weaken, but rather strengthen, the need for rigorous model-based analysis, in order to identify and critically discuss the sources for these differences. One approach to doing so is by comparing results from alternative modeling systems, as undertaken by the Economic Modeling Forum in Stanford (see for example Weyant 1999). One potential shortcoming of the cross-model comparison is that it overstrains the non-technical reader, who needs to be familiar with not only one but various models, including the respective differences in parametrization, which are often not very transparent.

In this chapter we have taken a different approach. We endorsed the use of a *single* analytical framework, in our case the computable general equilibrium (CGE) approach. We then laid out in detail a generic multi-sector, multi-region CGE model of the world economy to study the economic and environmental impacts of alternative emission abatement scenarios. Simulations focused on the implementation of the Kyoto Protocol, but the issues addressed are relevant for any future agreements on quantified emission limitation and reduction objectives. An extensive sensitivity analysis has been performed to provide insights as to how differences in underlying assumptions affect the model results. The main conclusions emerging from our modeling exercise on the implementation of the Kyoto Protocol can be summarized as follows:

1. Emission constraints as mandated under the Kyoto Protocol induce non-negligible adjustment costs to OECD countries. The main reason is that the emissions of these countries have grown significantly along the baseline compared to 1990 levels. The Kyoto targets, which are stated with respect to 1990, therefore translate into much higher effective carbon abatement requirements with respect to BaU emission levels in 2010. At the domestic level, OECD countries must impose rather high carbon taxes to comply with their commitments; the tax-induced reallocation of resources such as fuel shifting or energy savings causes efficiency costs, which translates into a loss in real income for households in industrialized countries. These mechanisms highlight the importance of the underlying

baseline on economic and emission growth, as it defines the size of the reduction and the magnitude of the abatement costs required for meeting a particular target.

2. Abatement in OECD countries produces significant spillovers to non-abating regions through induced changes in international prices, i.e. the terms of trade. Most important are adjustments in international markets for crude oil and coal. The cut-back in global demand for these fossil fuels implies a significant drop in their prices, providing economic gains to fossil fuel importers and losses to fossil fuel exporters. These effects explain most of the welfare impacts on developing countries.
3. Sub-global action on behalf of Annex B countries has important implications for comparative advantage and the pattern of trade for energy-intensive goods. Even though energy costs do not constitute a large share of value-added in energy-intensive production, the unilateral cost increase in OECD countries diminishes competitiveness sufficiently to induce large changes in trade flows.
4. The drop in international fuel prices and changes in the pattern of trade for energy-intensive goods induces global leakage of more than 20% for the NOTRADE scenario in which Annex B countries meet their Kyoto reduction targets solely by domestic action. The magnitude of leakage is very sensitive to the representation of fossil fuel markets. In our analysis, we assumed homogeneity of crude oil and coal from different origins based on empirical evidence of low transport costs. This significantly increases leakage, as compared to a setting in which crude oil and coal are distinguished as imperfect substitutes by region of origin.
5. Not surprisingly, international trade in emissions significantly reduces the global costs of compliance to Kyoto through the equalization of marginal abatement costs across regions. What is surprising, however, is that the cost reduction associated with a shift from Annex B trading to global emissions trading is much smaller than that generated by the move from the no-trade scenario to Annex B trading. The reasoning behind this, is that hot air from CEA and FSU accounts for a larger share of welfare gains achievable through permit trading. In particular, FSU can trade in huge amounts of abundant emission rights since its BaU emissions are far below its Kyoto commitment. Trade in emission rights makes FSU substantially better off even as compared to the BaU. Among Annex B countries, only the OECD regions benefit from global emissions trading as compared to restricted Annex B trading. Global trading increases the supply of

emission abatement from abroad, which further relieves the Kyoto emission constraint on OECD countries. FSU and CEA suffer from a decline in the permit price, which implies a substantial loss in their income from permit sales. If we include transaction costs for permit sales from non-Annex B countries to Annex B regions, the welfare implications of global trading for OECD countries on the one hand and FSU as well as CEA on the other hand, become attenuated. In terms of environmental effectiveness, it is interesting to see that avoided leakage through global trading is just compensated by hot air as compared to the no-trade case.

6. It is now commonly accepted that the gross costs of emission abatement can be substantially reduced when revenues accruing from emission taxes or permit sales are used for revenue-neutral cuts in existing distortionary taxes. In our simulations, we addressed this issue in a very stylized way, indicating the scope for a double dividend of GHG abatement policies.
7. Sensitivity analyses on the values of key elasticities confirm economic intuition that global economic adjustment to emission constraints is cheaper, the better the indirect substitution possibilities for fossil fuels. The more enlightening insight from this section of sensitivity analyses is that the distributional impacts across regions may be quite different. If we were to believe, for example, that crude oil supply reacts in a more price-elastic way to cuts in global oil demand, this would imply smaller gains for crude oil importers but smaller losses to oil exporters. Trade elasticities on non-energy markets are also a major determinant of the secondary terms-of-trade effect, which may significantly alter the direct (primary) economic impacts of abatement policies. Furthermore, the choice of these elasticities affects the environmental effectiveness of sub-global abatement action, which may have important implications for the design of unilateral abatement policies, such as tax exemptions or tax cuts for energy-intensive industries to reduce leakage.

Most of the insights listed above may not be new to those readers who have followed the scientific and policy debate on climate change during the last few years. However, we hope that they have nevertheless benefited from the concise and stringent treatment of key policy issues within one single transparent modeling framework.

We close with several caveats. Although our model captures important aspects of economic responses to global carbon emission constraints, it is nonetheless only a crude approximation of the real world's technologies, preferences, factor endowments etc. We therefore caution against too literal an interpretation of the numerical results. Second, there are several aspects missing from the analytical framework presented above that are potentially important, such as the incorporation of non-CO_2 gases and sinks, the incorporation of endogenous investment responses in a dynamic setting with rational expectations, global capital mobility or induced technological change. Finally, we want to stress that quantitative economic models are not at all truth machines, but simply a means of comparing various options along with their price tags. They cannot resolve fundamental political or philosophical conflicts; in the end, it is up to society and governments to decide what to do. Nonetheless, we are convinced that quantitative estimates based on the rigorous and deliberate use of economic models can provide useful decision support for the climate policy debate.

NOTES

1. The equivalent (dual) formulation is to achieve the greatest improvement in some environmental target for a given expenditure of resources.
2. One exception is ETA-MACRO (Manne 1981) and its derivatives. It combines a fairly detailed linear technology model of energy supply with a highly aggregated (one-sector) macroeconomic model.
3. In fact, recent developments in the solution of nonlinear systems of inequalities (Dirkse and Ferris 1995) have promoted the synthesis of bottom-up and top-down models within one consistent general equilibrium framework (see Böhringer 1998b).
4. The terms of trade are generally measured as the ratio of a country's exports to its imports in value terms.
5. Böhringer and Rutherford (forthcoming) provide a method for decomposing the primary and secondary effects in a multi-regional general equilibrium framework.
6. In bottom-up models, technological innovation can be captured through explicit technologies. However, the evolution of future technologies is typically taken as exogenous inputs from expert projections and not treated as an endogenous variable.
7. With exogenous technical change, it is generally cheaper to wait for better technologies to come along.
8. For surveys on the use of numerical models in other fields, see Shoven and Whalley (1992), Peireira and Shoven (1992), Kehoe and Kehoe (1994), or Fehr and Wiegard (1996).
9. For the sake of simplicity, the symbols α, β, ϕ and θ are used throughout the model description to denote the technology coefficients.
10. The one exception is the TCOST scenario, in which we allow for global carbon trading, in order to have a meaningful base for comparison.
11. Among other reasons, this may have motivated the recent withdrawal of the USA from the Kyoto Protocol.
12. The simple reason is that the higher the BaU energy prices, the larger the required absolute price increases to achieve a given percentage change in prices.
13. We address this question in a very crude manner in Section 4.8.

14. The Kyoto Protocol explicitly acknowledges the importance of international spillovers in stipulating that unilateral abatement policies should minimize adverse trade effects on other Parties (UNFCCC 1997, Article 2, 3). Böhringer and Rutherford (2001) present a simple decomposition technique of the total welfare effect of carbon abatement policies into a primary domestic market effect (at constant international prices) and a secondary international spillover impact as a result of changes in international prices.
15. These concerns may be justified on cost-effectiveness grounds when the relocation of energy-intensive industries to non-abating countries significantly reduces the environmental effectiveness of sub-global abatement policies. However, a natural consequence of decreasing carbon emissions is to reduce carbon-intensive production (and consumption) – an obvious point often missed by policy makers.
16. Unresolved issues are, *inter alia*, the time when trading might start, the definition of participants and gases that might be traded, the establishment of the rules and procedures for trading, the institutional set-up and the regulations regarding monitoring, verification and an ultimate enforcement of the rules.
17. Note that – in contrast to textbook partial equilibrium analysis – this need not be the case in a general equilibrium framework where, at the single country level, direct gains from emissions trading can be more than offset from indirect losses through the deterioration of a country's terms of trade (see e.g. Böhringer 2001).
18. More specifically, we use the US labor market as the resource input involved and scale time requirement such that the additional cost of trading is equal to $US5, $US10 and $US20 respectively. The 'closure' of transaction costs via the huge US labor market has only negligible general equilibrium effects on the aggregate labor demand and thus the equilibrium price for US labor.
19. Remember that the larger part of potential efficiency gains from trading is due to sales from FSU and CEA – see Section 4.3.
20. One notable exception is Böhringer, Jensen and Rutherford (2000), who focus on the economic implications of alternative BaU assumptions on the magnitude and distribution of abatement costs across EU countries.
21. The implications of changes in coal supply elasticities are analogous. For the sake of brevity, the respective results are omitted here.

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