Economic Impacts of Climate Change Policy

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A Quantitative Analysis

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Meiner Frau

Claudia

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1 Introduction

Global warming has received growing attention during the last decade. The accumulation of anthropogenic greenhouse gas (GHG) emissions in the atmosphere is likely to lead to significant climate changes. In order to avoid potentially larger adverse impacts, GHG emissions - most notably carbon dioxide (CO_2) released from fossil fuel use – must be drastically reduced in the future.

An economic assessment of climate change has to weigh the benefits from avoided undesirable consequences of global warming against the costs of greenhouse gas emission abatement. Given complete information, cost–benefit analysis could tell policymakers how much greenhouse gas 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 benefits of protecting against the negative effects of climate change. The chain of causality - from GHG emissions to ambient concentrations of greenhouse gases in the atmosphere to temperature increase to physical effects such as climatic and sea level changes - is highly complex. Hence, more attention is given to analyzing the costs rather than the benefits of climate change policy.

Rational climate policy decision-making requires quantitative assessment, i.e. the use of analytical models that mimic the potential economic impacts of alternative emission reduction policies. A large number of models has been developed to investigate climate change policies that aim at achieving GHG emission trajectories suggested by natural science in a precautionary approach. In assessing alternative GHG abatement strategies the magnitude as well as the distribution of the associated adjustment costs is of major policy relevance. Because of the potentially large costs of ambitious climate change strategies, cost-effective implementation is essential in gaining broader acceptance. Besides efficiency in terms of overall abatement costs, equity in terms of a ‘fair’ distribution of these costs across countries, sectors or agents for alternative policy strategies is crucial.

This thesis contains a selection of essays dealing with the quantitative economic impact analysis of climate change policy. It comprises detailed modeling of the economic adjustment to GHG emission constraints and provides valuable information to make rational policy choices. Different quantitative approaches are employed to warrant the appropriate analysis of selected policy aspects: computable general equilibrium (CGE) modeling, partial equilibrium modeling and econometrics. The thesis is organized in seven chapters. Chapter 2 briefly discusses central issues in the economics of climate change. It motivates CGE modeling as a powerful tool to assess these issues in a consistent economy-wide framework and demonstrates its usefulness along illustrative calculations of the potential economic consequences induced by exogenous emission reduction constraints. The following chapters substantiate specific problems of climate policy. This requires extensions of the core CGE model as well as the additional use of partial equilibrium and econometric approaches. Chapters 3 and 4 investigate how the implications of emission constraints change when switching from the conventional perfect competition paradigm to the more realistic assumption of imperfect competition on good and permit markets. Chapters 5 and 6 present alternative modeling approaches to joint implementation (JI), which involves cross-border investments by industrialized countries to meet part of their domestic emission reduction targets through abatement activities of developing countries. Chapters 7 and 8 address methodological challenges for the model-based assessment of adjustment costs to emission regulation: the choice of costing concepts and the appropriate representation of technological change. Each chapter of the thesis is an independent piece of work and can be read separately. The different chapters contain an introduction that motivates the issues under investigation, relates them to the literature, and highlights the contributions made. Therefore, we can confine ourselves in this introduction to providing a brief summary of each essay.

Chapter 2 analyses the costs of compliance with the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) which marks a milestone in international climate policy. For the first time, industrialized countries - listed in Annex B of the Protocol - agreed to limit their emissions of greenhouse gases. The chapter starts out with a short summary of major policy issues surrounding the Kyoto deal and provides a literature synthesis of results from former model-based simulation analyses. Then, a comparative-static multi-region, multi-sector CGE model for the cost analysis of alternative climate change policies is described in analytical detail. The model is used to deliver quantitative insights into various major issues of the international climate policy debate. Simulations indicate that emission constraints as initially mandated under the Kyoto Protocol induce non-negligible adjustment costs to most Annex B countries. For purely domestic action, several Annex B countries would require 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 translate into a loss of real income. Unilateral abatement in Annex B countries has important implications for comparative advantage and the pattern of trade for energy-intensive goods including significant carbon leakage to non-abating regions. It produces important spillovers to non-abating regions through changes in international prices, i.e. the terms of trade. Most important is the drop in international fuel prices due to the decline in global energy demand providing terms-of-trade gains for fuel importing countries and losses to fuel exporters. International trade in emissions not only reduces carbon leakage but substantially reduces the global costs of compliance to Kyoto through the equalization of marginal abatement costs across regions. The robustness of results with respect to changes in the values of key elasticities as well as other major assumptions, such as the baseline growth path or the scope of the abatement coalition (Kyoto with and without the US) are then explored. The sensitivity analysis helps to create an understanding of key assumptions which determine the quantitative model results and the policy conclusions to be drawn.

Chapter 3 shows that the effects of environmental taxes may depend crucially on the market structure. Contrary to the perfect-competition paradigm usually underlying the impact analysis of environmental taxation in open economies, the more recent trade literature emphasizes the importance of imperfect competition and economies of scale. These features are incorporated in the open economy CGE model of Chapter 2. The extended model that allows for a switch between the perfectly competitive and imperfectly competitive market setting is then applied to examine the effects of a unilaterally imposed carbon tax on the German economy. It is found that induced structural change in favor of the less energy-intensive, more labor-intensive industries is more pronounced under imperfect competition than under perfect competition. The logic behind this result is that carbon taxes affect comparative advantage leading to shifts in the demand structure and the effective demand elasticities for outputs of industries. The elasticity of demand is typically higher for sales abroad than for sales in domestic markets. Therefore, industries which gain in comparative advantage and sell a larger portion of their output abroad will face a higher overall demand elasticity. This reduces market power, drives firms out of the market, and raises economies of scale. The reverse applies to industries which lose in comparative advantage: Their effective demand elasticity drops and economies of scale get reduced. As a result, the change in relative costs across industries is enhanced, and so is induced structural change. At the macroeconomic level, the total costs of environmental regulation under imperfect competition can be higher or lower than those under perfect competition depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail. The costs to the German economy turn out to be higher, since the aggregate changes in economies of scale across imperfectly competitive sectors are negative.

Chapter 4 analyses the potential implications of non-competitive supply behavior on international markets of tradable permits for the compliance costs of Annex B countries and global carbon emission reduction under the Kyoto Protocol. The analysis accounts for recent modifications of the Kyoto Protocol, i.e. the generous accounting of sinks credits and US withdrawal. A simple back-of-the-envelope calculation indicates that withdrawal of the US - as the biggest single potential buyer of international emission permits – implies excess supply of emission rights due to large amounts of hot air that has been ceded to the Former Eastern Bloc under the Kyoto Protocol in excess of their anticipated business-as-usual emissions. Assuming perfect competition on permit markets, permit prices and environmental effectiveness of the Protocol vis-à-vis the business-as-usual would drop to zero. In this case Annex B countries that would face binding Kyoto emission constraints under purely domestic action could meet their targets through hot air credits at zero costs, while hot air countries, i.e. the former Soviet Union (FSU) and the Eastern European countries (EEC), lose all their revenues from permit sales. However, given the small number of sellers on the market, it seems rather reasonable to assume that suppliers of permits exert market power in order to maximize their revenues from permit sales. Simulations with a partial equilibrium model of the permit market show that the overall compliance costs of Annex B buyer regions could be twice as much in the case of FSU-EEC cooperation than for the FSU monopoly case. But no matter how market power is exerted, all Kyoto-constrained Annex B regions will always be better off with emissions trading than without trading at all. Moreover, curtailing permit supply by market power substantially reduces the amount of hot air sales and effects actual domestic abatement efforts by permit buyer countries. Thus, overall environmental effectiveness increases. Sensitivity analyses on key parameters of the partial equilibrium model support the robustness of the quantitative results.

Chapter 5 investigates in more detail the potential benefits from joint implementation of GHG emission abatement between industrialized and developing countries that may complement domestic actions by Annex B countries. Germany and India serve as an example. Within its climate policy strategy, Germany aims at reducing its carbon emissions by 25 percent in 2005 as compared to 1990 emission levels. To achieve this goal, the government has launched an environmental tax reform which entails a continuous increase in energy taxes in conjunction with a revenue-neutral cut in non-wage labor costs. This policy is supposed to yield a double dividend, reducing both, the problem of global warming and high unemployment rates. As an alternative to a purely domestic policy as envisaged by original environmental tax reform (ETR) proposals, Germany might consider entering joint implementation with developing countries such as India where Germany pays emission reduction abroad rather than meeting its reduction target solely by domestic action. It is investigated whether an ETR in Germany cum JI with the Indian electricity sector provides employment and overall efficiency gains as compared to an ETR stand-alone. The quantitative framework for the analysis builds on the CGE model of Chapter 2 extended for aspects of efficiency improvements through capital transfers. The main finding is that ETR cum JI provides a superior solution to both countries vis-à-vis the ETR stand-alone case. JI largely offsets the adverse effects of carbon emission constraints on the German economy. It significantly lowers the level of carbon taxes and thus reduces the total costs of abatement as well as negative effects on labor demand. In addition, JI triggers direct investment demand for energy efficient power plants produced in Germany. This provides positive employment effects and additional income for Germany. For India, joint implementation equips its electricity industry with scarce capital goods leading to a more efficient power production with lower electricity prices for the economy and substantial welfare gains.

Chapter 6 assesses how investment risks to project-based (JI) emission crediting between industrialized countries and developing countries affect the magnitude and distribution of efficiency gains. Based on the multi-region partial equilibrium model developed in Chapter 4, it is confirmed that project-based emission crediting in developing countries drastically reduces the overall costs of emission constraints for industrialized countries. At the same time, it provides considerable income to developing countries with larger low-cost abatement options. The incorporation of country-specific investment risks induces only small changes in the magnitude and distribution of benefits from project-based emission trading vis-à-vis a situation where investment risks are absent. Only if investors are highly risk-averse will the differences in risk across developing countries become more pronounced and induce a non-negligible shift in comparative advantage from high-risk developing countries to low-risk developing countries. Although the total amount of emission credits across all developing countries will distinctly shrink for this case (i.e. domestic abatement shares in industrialized countries increase), the low-risk developing countries may attract higher project volumes at the expense of high-risk countries and may also benefit from higher effective prices per emission credit compared to a simulation without risk. The opposite applies to high-risk countries. The welfare implications of risk incorporation for industrialized countries are unambiguously negative. Sensitivity analysis with respect to the magnitude of investment risks highlights the relevance of risk aspects. When investors go for high safety of returns and perceive substantial differences in project-based risks across countries, only very cheap projects in high-risk developing countries will be realized, and the associated benefits to high-risk countries may fall close to zero, while low-risk developing countries will fare even better.

Chapter 7 emphasizes that a labor market policy of recycling tax revenues from an environmental tax to lower employers' non-wage labor cost depends on how the costs of labor are measured in CGE models. It proposes an approach which combines neoclassical substitutability and fixed factor proportions. This cost-price approach uses Leontief partially fixed factor proportions to identify both a disposable (or variable) part and a bound (or fixed) portion of each input. The true cost, or cost price, of any input consists of its own price plus the costs associated with the portion of that input bound to other inputs. As an example, the cost of an additional worker includes not just salary, but also the costs of inputs tied to the worker (e.g. office equipment, electricity, material, etc.). Within the cost-price framework, the demand for an input can be separated into a committed component that is linked to the use of other inputs and a disposable component which is free for substitution. At one extreme, when the disposable quantities of all inputs equal zero, no factor substitution is possible and the cost-price approach reduces to the Leontief fixed-proportion case. At the other extreme, when the committed quantities of all inputs are zero, the neoclassical model is relevant and the cost-price of any input equates the market price. Cost-share equations in cost prices are econometrically estimated for German industries and then cost prices instead of market prices are used to investigate the double dividend hypothesis. Quantitative analyses with the adapted CGE model for Germany prove the importance of alternative cost-price assumptions with respect to the 'existence' of a double dividend from environmental taxation. In the simulations, carbon taxes are levied to achieve a certain level of CO_2 emission reduction; additional tax revenues are used to cut non-wage labor cost. The simulations are based either on the market price of labor or on the user cost of labor. Under the first approach a double dividend occurs but not under the second one. This result makes the economist's adage to policy makers clear that the outcome of a policy is ambiguous and depends on assumptions made. However, the point - that user costs of labor matter more than the normal wage costs - is intuitively attractive when arguing about the double dividend hypothesis.

Chapter 8 provides an overview of how technological change is represented in large-scale energy-economy-environment models for applied policy analysis. Numerous modeling studies have shown the sensitivity of mid- and long-run climate change mitigation cost projections to assumptions about technology. Technological change is in general considered to be a non-economic, exogenous variable in energy-economy models. Economic activities and policies have then no impact on research, development, and diffusion of new technologies. However, there is overwhelming evidence that technological change is not an exogenous variable, but to an important degree endogenous, induced by needs and pressures. Hence, a new generation of environmental-economic models treats technological change as endogenous, i.e. responding to socio-economic (policy) variables, e.g. prices, investment in R&D, or cumulative production. This chapter gives first a taxonomy of different model types (bottom-up, top-down, integrated assessment models). Then, exogenous specifications of technical change such as the autonomous energy efficiency parameter, the specification of backstop technologies and technology snapshots are explored. Even though the theory of induced technological change is still in development at present, three main approaches to incorporate induced technical progress can be identified: (i) corporate investment in research and development, (ii) spillovers from R&D and (iii) technology learning, especially learning-by-doing. It is shown how technical change is accounted for in different energy-environmental-economic models. The few results from applied modeling indicate that the incorporation of induced technological change tends to reduce the costs of environmental policy, accelerates abatement and may lead to positive spillover and negative leakage.

2 Assessing the Kyoto Protocol [*]

2.1 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[1] 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

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[*] This chapter is based on the papers 'Economic Impacts of Carbon Abatement Strategies', with C. Böhringer, in: C. Böhringer, M. Finus and C. Vogt (eds.), *Controlling Global Warming - Perspectives from Economics, Game Theory and Public Choice*, Cheltenham: Edward Elgar (New Horizons in Environmental Economics), 98-172, 2002, and 'Assessing the Costs of Compliance: The Kyoto Protocol', with C. Böhringer, in: *European Environment*, 12, 1-16, 2002.

[1] Industrialized countries that, as parties to the United Nations Framework Convention on Climate Change (UNFCCC), have pledged to reduce their GHG emissions by the year 2000 to 1990 levels are listed in Annex I of the Convention. They include both countries belonging to the Organisation for Economic Co-operation and Development (OECD) and countries with economies in transition (EITs). Countries taking on legally binding commitments under the Kyoto Protocol are listed in Annex B of the Protocol (UNFCCC, 1997). All of the Convention's Annex I Parties - with the exception of Belarus and Turkey - have made commitments under the Kyoto Protocol's Annex B.

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 often come as black boxes. Without knowing the theoretical model, all we 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 2.2 provides a short summary of relevant policy issues and presents the main results from applied modeling. Section 2.3 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 2.4 provides applications of this model to selected issues of the international climate policy debate. Section 2.5 summarizes and concludes.

2.2 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 to 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.[2] 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 2.4, 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.

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[2] The equivalent (dual) formulation is to achieve the greatest improvement in some environmental target for a given expenditure of resources.

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 2.3. 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 2.4. 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, 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. One will notice that we have omitted several topics which are not necessarily less important than those explicitly addressed in this chapter. Among these topics are offsets from CO_2 sinks (see Stavins, 1999; Reilly et al., 1999), the incorporation of non-CO_2 GHG mitigation options (see MacCracken et al., 1999; Reilly et al., 1999; Burniaux and Martins, 2000) and implications from intertemporal flexibility (see Richels and Sturm, 1996; Richels et al., 1996; Tol, 1999). Other important issues are discussed in later chapters, e.g. the effects of market power on good markets

(Chapter 3) and permit markets (Chapter 4), the implications of the project-based Kyoto instruments being mechanisms of technology transfer (Chapter 5) and the consequences of risks in associated cross-border investments (Chapter 6).

2.2.1 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 assumptions on the status quo, i.e. the baseline, of the economic system without exogenous policy interference (see Section 2.2.1.1). Another major source for deviations in cost estimates are differences in the scope of economic interactions that are captured by the studies (see Section 2.2.1.2). Chapter 8 provides an extensive overview of how technological change, which is also 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, is represented in applied environment-economy models. The awareness of all these determinants for economic impacts of exogenous policy changes is a prerequisite to properly understanding model results and drawing appropriate conclusions. Hence, a major task for applied modeling is to reveal by means of sensitivity analysis the importance of subjective judgements, which are implicit in the choice of the baseline, system boundaries and system relationships, for quantitative model results.

2.2.1.1 Baseline assumptions

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. Böhringer et al. (2000a) study the implications of alternative baseline projections on the magnitude and distribution of emission abatement costs under the Kyoto Protocol within the EU.

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; 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, 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).

2.2.1.2 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 in Chapter 8.

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.[3] 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, they simply relate to the level of aggregation and the scope of *ceteris paribus* assumptions.[4]

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[3] 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.

[4] 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).

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. 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),[5] imply a secondary benefit or burden that can significantly alter the economic implications of the primary domestic policy. 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

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[5] The terms of trade are generally measured as the ratio of a country's exports to its imports in value terms.

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; Bernstein et al., 1999; McKibbin et al., 1999; Tulpulé et al., 1999; Montgomery and Bernstein, 2000).

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 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 change 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 (Barker and Johnstone, 1998; Ekins and Speck, 1998). The use of flexibility instruments reduces the competitive advantage of non-Annex B countries (see also Section 2.4.3).

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) (see Welsch, 1994 for a theoretical analysis). Thirdly, carbon leakage may be induced by changes in regional income (and thus energy demand) due to terms of trade changes (Rutherford, 1995a). 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. 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; Paltsev, 2000a).

2.2.2 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 has only minor effects on the global costs of abatement when transactions costs of exchange are nil and there are no important income effects. A very similar efficient (cost-effective) outcome is reached for different initial permits allocations after all gains from trade are realized, i.e. marginal abatement costs across countries are equalized (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; Rose et al., 1998; Ringius et al., 1999): under the egalitarian criterion it is assumed that all nations have an equal right to pollute or be protected from pollution. Emission rights are allocated in proportion to population (‘equal per capita emissions’). Under the sovereignty criterion current emissions constitute a status quo right now and emission rights are distributed accordingly (‘grandfathered’). 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 (Edmonds et al., 1995; Manne and Richels, 1995; Rose and Stevens, 1998; Rose et al., 1998; 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.

The separability of efficiency and equity under marketable permits allows us to concentrate on the former in our model simulations in Section 2.4. Equilibrium abatement costs are only slightly affected 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).

2.3 A CGE Model for Carbon Abatement Policy Analysis

Carbon abatement policies not only cause direct adjustments of fossil fuel markets, but they also produce indirect spillovers to other markets that, in turn, feed back to the economy. General equilibrium modeling 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 and 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; Conrad, 1999, 2001).[6]

This section outlines the main characteristics of a static general equilibrium model of the world economy designed for the medium-run economic analysis of carbon abatement constraints. It is a well-known Arrow-Debreu model of the interaction of consumers and producers in markets. Consumers in the model have a primary exogenous endowment of the factors of production 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. Three classes of conditions characterize the competitive equilibrium in the model: zero profit conditions for production activities, market clearance conditions for each primary

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[6] See Shoven and Whalley (1984) for an introduction to CGE modeling. For surveys on the use of numerical models in other fields, see Peireira and Shoven (1992), Shoven and Whalley (1992), Kehoe and Kehoe (1994), or Fehr and Wiegard (1996).

factor and produced good and income definition equations with respect to the incomes of the economic agents. In equilibrium, (relative) prices are such that market demand equals market supply for each factor and commodity. Profit maximization under constant returns to scale technology implies that no activity does any better than break even at equilibrium prices. It determines production levels in each industry in equilibrium. The model is a system of simultaneous, non-linear equations with - after the numeraire is fixed - 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 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. The model 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 (COL), natural gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). The non-energy sectors include important carbon-intensive and energy-intensive industries that are potentially most affected by carbon abatement policies. There are four non-energy sectors: agricultural production (AGR), production of energy-intensive goods (EIS), investment goods (CGD), and a macro commodity which aggregates all other non-energy goods (other manufactures and services, OTH). The primary factors in the model are labor (L), physical capital (K) and fossil-fuel resources (R). Primary factor endowments are exogenous. Factor markets are assumed to be perfectly competitive. In our baseline scenario, labor and capital are treated as perfectly mobile across sectors. Fossil-fuel resources are sector-specific. Factors are immobile between regions. All agents are price takers, i.e. there are no market imperfections.[7] Table 2.1 summarizes the regional, sectoral, and factor aggregation of the model.

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[7] The implications of market power on good markets and permit markets are analyzed in Chapter 3 and Chapter 4, repectively.

Table 2.1 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

2.3.1 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 quantities of primary factors *k* (indexed by *f*), intermediate inputs *x* from other sectors and production levels *y* in order to maximize profits, given input and output prices. The profit maximization problem of a competitive firm *i* in region *r* is then:

$$\underset{y_{ir},\vec{x}_{\cdot ir},\vec{k}_{\cdot ir}}{Max} \quad p_{ir}\cdot y_{ir}-\sum_{j} p_{jr}\cdot x_{jir}-\sum_{f} w_{fr}\cdot k_{fir} \quad \text{s.t.} \quad y_{ir}\leq\varphi_{ir}\left(\vec{k}_{ir},\vec{x}_{ir}\right), \tag{2.1}$$

where p_{ir} and w_{ir} are the prices for goods and factors, respectively, and $\varphi_{ir}\left(\vec{k}_{ir},\vec{x}_{ir}\right)$ the production functions (assumed to be linear homogenous in the model). When the profit maximization problem has a solution for given prices, the profit function $\Pi_{ir}\left(\vec{p}_r,\vec{w}_r\right)$ gives the maximum profits of firm *i* in region *r* as a function of input and output prices. A necessary condition for profit maximization is cost minimization, i.e. there is no way to produce the same amount of output at a lower total input cost. The cost function $C_{ir}\left(\vec{p}_r,\vec{w}_r,y_{ir}\right)$ relates the minimum possible total costs of producing y_{ir} to the positive input prices, technology parameters, and the output quantity.

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). Firms are indifferent about the level of output at which they produce. Profit maximization under constant returns to scale implies the equilibrium condition:

$$\pi_{ir}\left(\vec{p}_r,\vec{w}_r\right) = p_{ir}-c_{ir}\left(\vec{p}_r,\vec{w}_r\right) = 0 \quad \text{(zero profit condition)}, \tag{2.2}$$

where c_{ir} are the unit cost functions and π_{ir} the unit profit functions, respectively.

Demand functions for goods and factors can be derived by Shephard's Lemma. It states 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. Hence, the intermediate demand for good *j* in sector *i* is:

$$x_{jir} = \frac{\partial C_{ir}\left(\vec{p}_r, \vec{w}_r, y_{ir}\right)}{\partial p_{jr}} = Y_{ir} \cdot \frac{\partial c_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial p_{jr}}, \tag{2.3}$$

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

$$k_{fir} = \frac{\partial C_{ir}\left(\vec{p}_r, \vec{w}_r, y_{ir}\right)}{\partial w_{fr}} = Y_{ir} \cdot \frac{\partial c_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial w_{fr}}. \tag{2.4}$$

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

$$a^x_{jir} = \frac{x_{jir}}{Y_{ir}} = \frac{\partial c_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial p_{jr}} = -\frac{\partial \pi_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial p_{jr}}, \quad \text{and} \tag{2.5}$$

$$a^k_{fir} = \frac{k_{fir}}{Y_{ir}} = \frac{\partial c_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial w_{fr}} = -\frac{\partial \pi_{ir}\left(\vec{p}_r, \vec{w}_r\right)}{\partial w_{fr}}. \tag{2.6}$$

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). Each intermediate input represents a composite of domestic and imported varieties as described below (Armington assumption). Two types of production functions are employed: those for fossil fuels (*v* = COL, CRU, GAS) and those for non-fossil fuels (*n* = AGR, CGD, EIS, ELE, OIL, OTH).

Figure 2.1 illustrates the nesting structure in *non-fossil fuel production*. In the production of non-fossil fuels *n*, 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. Material *i* for use in sector *n* in region *r* is thus a constant share of sector n output Y_{nr}. At the second level, a CES function describes the substitution possibilities between the aggregate energy input *E* and the value-added aggregate *KL*:[8]

$$Y_{nr} = \min\left\{(1-\theta_{nr})M_{nr}, \theta_{nr}\phi_{nr}\left[\alpha_{nr}E_{nr}^{\rho^{KLE}} + \beta_{nr}KL_{nr}^{\rho^{KLE}}\right]^{1/\rho^{KLE}}\right\}, \tag{2.7}$$

where $\sigma^{KLE} = 1/(1-\rho^{KLE})$ is the elasticity of substitution between energy and the primary factor aggregate and θ is the input (Leontief) coefficient. When the energy value share of an industry, α_{nr}, is small, the elasticity of substitution between the value added aggregate and the composite energy good, σ^{KLE}, is nearly equal to the own price elasticity of demand for energy. This elasticity determines how difficult it is for a region to adjust its production processes in response to changes in energy prices. Higher values imply that a region can more easily substitute value added for energy when the price of energy increases. Finally, at the third level, capital and labor factor inputs trade off with a constant elasticity of substitution $\sigma^{KL} = 1/(1-\rho^{KL})$:

$$KL_{nr} = \phi_{nr}\left[\alpha_{nr}K_{nr}^{\rho^{KL}} + \beta_{nr}L_{nr}^{\rho^{KL}}\right]^{1/\rho^{KL}}. \tag{2.8}$$

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 $\sigma^{E} = 1/(1-\rho^{E})$ at the top nest:

$$E_{nr} = \phi_{nr}\left[\alpha_{nr}A_{ELE,nr}^{\rho^{E}} + \beta_{nr}FF_{nr}^{\rho^{E}}\right]^{1/\rho^{E}}. \tag{2.9}$$

---

[8] For the sake of simplicity, the symbols α, β, ϕ and θ (and $\hat{\alpha}$, $\hat{\beta}$, $\hat{\phi}$ and $\hat{\theta}$) are used throughout the model description to denote the technology coefficients. We assume constant returns to scale.

The primary energy composite *FF* is defined as a CES function of coal and the composite of refined oil and natural gas with elasticity $\sigma^{COA} = 1/(1-\rho^{COA})$. 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 $1-\theta$, respectively:

$$FF_{nr} = \phi_{nr}\left[\alpha_{nr} A_{COA,nr}^{\rho^{COA}} + \beta_{nr}\left(A_{OIL,nr}^{\theta_{nr}} \cdot A_{GAS,nr}^{1-\theta_{nr}}\right)^{\rho^{COA}}\right]^{1/\rho^{COA}} . \qquad (2.10)$$

The hierarchical structure of demand admits two elasticities which govern inter-fuel substitution: σ^{COA} determines the ease with which coal can substitute for liquid fuels, and σ^{LIQ} determines the potential for substitution between oil and gas.

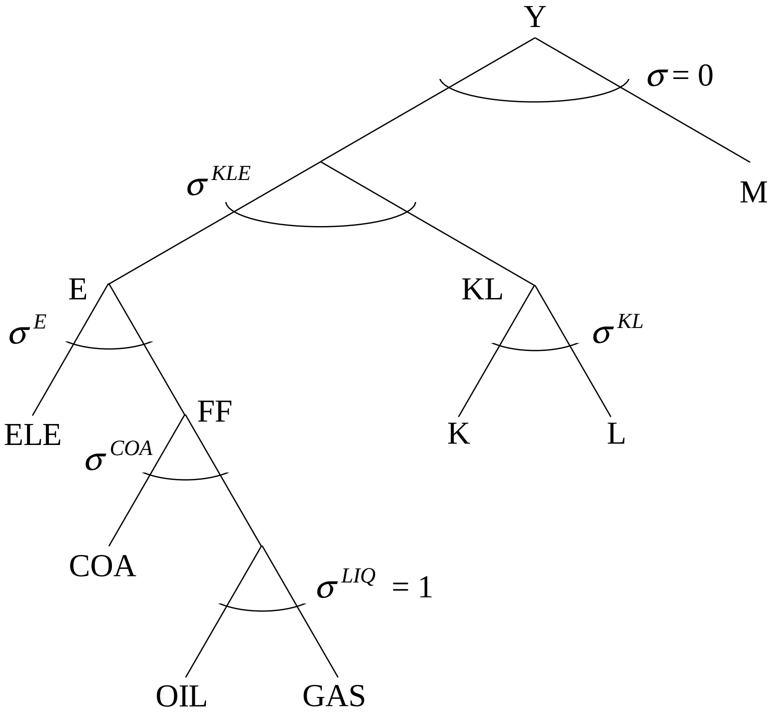

Figure 2.1 Nesting structure of non-fossil fuel production

Production of *fossil fuels v*, i.e. crude oil, gas, and coal, has the structure shown in Figure 2.2. It is characterized by the presence of a fuel-specific factor of production R_{vr} that represents the fuel resource in each region. The specific resource provides positive profits (rents) to the owners of the fixed resource, i.e. the representative agent in region *r*.

Mine managers minimize production costs subject to the technology constraint:

$$Y_{vr} = \phi_{vr}\left[\alpha_{vr} R_{vr}^{\rho_{vr}^f} + \beta_{vr}\left[\min\left(\theta_{vr}^K K_{vr}, \theta_{vr}^L L_{vr}, \theta_{vr}^E E_{vr}, \theta_{vr}^M M_{vr}\right)\right]^{\rho_{vr}^f}\right]^{1/\rho_{vr}^f}. \qquad (2.11)$$

The substitution elasticity between the specific factor and the Leontief composite of capital-labor-energy-material at the top level is $\sigma_{vr}{}^f = 1/(1-\rho_{vr}{}^f)$. This substitution elasticity is calibrated consistently with an exogenously given supply elasticity for exhaustible energy ε_{vr} according to:

$$\varepsilon_{vr} = \frac{1-\gamma_{vr}}{\gamma_{vr}}\sigma_{vr}^f, \qquad (2.12)$$

where γ_{vr} is 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 it is low in regions with less accessible resources (Babiker et al., 2001).

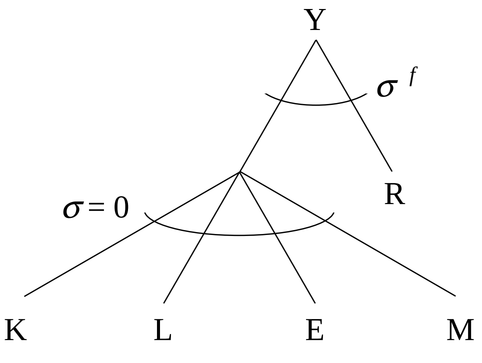

Figure 2.2 Nesting structure for fossil fuel production

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. As an example, we derive the variable input coefficients for labor and capital in non-fossil fuel production, a_{nr}^{L} and a_{nr}^{K}. The input coefficients for labor and capital in fossil fuel production, a_{vr}^{L} and a_{vr}^{K}, and the input coefficients for intermediate demand, a_{jir}^{Y} (= A_{jr}/Y_{ir}), can be determined in an analogous manner.

The total cost function C^{KL} that reflects the same production technology as the CES production function for value added *KL* in non-fossil fuel production given by Equation (2.8), is:

$$C_{nr}^{KL}\left(PK_{nr}, PL_{nr}, KL_{nr}\right) = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} \cdot KL_{nr}\,, \tag{2.13}$$

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:

$$PKL_{nr} = \frac{1}{\phi_{nr}}\left[\alpha_{nr}^{\sigma^{KL}} PK_{nr}^{1-\sigma^{KL}} + \beta_{nr}^{\sigma^{KL}} PL_{nr}^{1-\sigma^{KL}}\right]^{1/\left(1-\sigma^{KL}\right)} = c_{nr}^{KL}\left(PK_{nr}, PL_{nr}\right). \tag{2.14}$$

Shephard’s Lemma gives the price-dependent composition of the value-added aggregate as:

$$\frac{K_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\alpha_{nr}\cdot\frac{PKL_{nr}}{PK_{nr}}\right)^{\sigma^{KL}}, \quad \frac{L_{nr}}{KL_{nr}} = \phi_{nr}^{\sigma^{KL}-1}\left(\beta_{nr}\cdot\frac{PKL_{nr}}{PL_{nr}}\right)^{\sigma^{KL}}. \tag{2.15}$$

In order to determine the variable input coefficients for capital and labor, $a_{nr}^{K} = K_{nr} / Y_{nr}$ and $a_{nr}^{L} = L_{nr} / Y_{nr}$, one has to multiply Equations (2.15) 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 in Equation (2.7) is:

$$PY_{nr} = \left(1-\theta_{nr}\right)PM_{nr} + \frac{\theta_{nr}}{\hat{\phi}_{nr}}\left[\hat{\alpha}_{nr}^{\sigma^{KLE}} PE_{nr}^{1-\sigma^{KLE}} + \hat{\beta}_{nr}^{\sigma^{KLE}} PKL_{nr}^{1-\sigma^{KLE}}\right]^{\frac{1}{1-\sigma^{KLE}}}. \tag{2.16}$$

The demand for the value added per unit of production is:

$$\frac{KL_{nr}}{Y_{nr}} = \theta_{nr}\, \hat{\phi}_{nr}^{\,\sigma^{KLE}-1} \left(\widehat{\beta}_{nr} \cdot \frac{PY_{nr}}{PKL_{nr}} \right)^{\sigma^{KLE}} , \tag{2.17}$$

where θ_{nr} is the *KLE* cost share in total production. The variable input coefficients for labor and capital are then:

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

$$a_{nr}^{K} = \theta_{nr}\, \phi_{nr}^{\sigma^{KL}-1}\, \hat{\phi}_{nr}^{\,\sigma^{KLE}-1} \left(\alpha_{nr} \cdot \frac{PKL_{nr}}{PK_{nr}} \right)^{\sigma^{KL}} \left(\widehat{\beta}_{nr} \cdot \frac{PY_{nr}}{PKL_{nr}} \right)^{\sigma^{KLE}} . \tag{2.18}$$

2.3.2 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 *m*. The agent is endowed with the primary factors of production *f* (natural resources used for fossil fuel production, labor and capital). The budget constraint equates the value of energy and non-energy consumption to wage income, earnings on the capital stock, rents on fossil energy production, and tax revenues. The household's problem is then:

$$\underset{\vec{d}_r}{Max}\ U_r\left(\vec{d}_r\right) \quad \text{s.t.} \quad m_r = \sum_f w_{fr}\,\bar{k}_{fr} + TR_r \ \geq \ \sum_i p_{ir} d_{ir} \ , \tag{2.19}$$

where U_r is the utility of the representative household in region *r*, d_{ir} denotes the final demand for commodities, $\bar{k}_{fr}$ is the aggregate factor endowment of the representative agent and TR_r are total tax revenues. The utility function in the model is linearly homogeneous: $U_r\left(\lambda \vec{d}_r\right)$ = $\lambda \cdot U_r\left(\vec{d}_r\right)$. This is a convenient cardinalization of utility, because percentage changes in the utility level *U* are then equivalent to percentage Hicksian equivalent variations in income and

U_r can be used directly as a welfare measure. The indirect utility function, $V_r\left(\vec{p}_r, m_r\right)$, says how much utility the consumer receives at his optimal choice at prices p and income m. The unit expenditure function $e_r\left(\vec{p}_r\right)$ (or utility price index PU) indicates the minimum level of expenditure required to reach unity utility. Market final demand functions are derived using Roy's Identity as:

$$d_{ir}\left(\vec{p}_r, m_r\right) = -\frac{\partial V_r\left(\vec{p}_r, m_r\right)}{\partial p_{ir}} \bigg/ \frac{\partial V_r\left(\vec{p}_r, m_r\right)}{\partial m_r}. \tag{2.20}$$

In our model, total income of the representative agent consists of factor income, revenues from taxes levied on output, intermediate inputs, exports, imports, final demand, and CO_2 taxes (TR) and a baseline exogenous capital flow representing the balance of payment deficits B less expenses for exogenous total investment demand. In our comparative-static framework, regional investment demand I is fixed at the reference level. The composite price for investment is $PI_r = \Sigma_i a_{ir}^I \cdot PA_{ir}$, where PA_{ir} is the price of the different inputs. The budget constraint of the representative agent is then given by:

$$INC_r = PL_r \cdot \overline{L}_r + PK_r \cdot \overline{K}_r + \sum_v PR_{vr} \cdot \overline{R}_{vr} + TR_r + \overline{B}_r - PI_r \cdot I_r = PU_r \cdot U_r \ , \tag{2.21}$$

where INC_r is the income level of the representative agent and PR_{vr} is the price of the fuel-specific resources.

Household preferences are characterized by a CES utility function in our model. Utility of the agent is represented as a CES consumption composite of an aggregate of energy goods EC and non-energy goods NEC. The CES utility function is:

$$U_r = \left[\alpha_r EC_r^{\rho^C} + \beta_r NEC_r^{\rho^C}\right]^{1/\rho^C}, \tag{2.22}$$

where the elasticity of substitution between the energy and the non-energy composites is given by $\sigma^C = 1/(1-\rho^C)$. End-use energy is composed of an (Armington) CES-aggregate of electricity and the various fossil fuels (*ec* = COL, GAS, ELE, OIL), while substitution patterns within the non-energy aggregate (*nec* = AGR, EIS, OTH) are reflected via a Cobb-Douglas function:

$$EC_r = \left(\sum_{ec} \phi_{ec,r} A_{ec,r}^{\rho^{EC}} \right)^{1/\rho^{EC}} \text{ and } NEC_r = \prod_{nec} A_{nec,r}^{\theta_{jr}} , \tag{2.23}$$

where the elasticity of substitution within the energy aggregate is given by σ^{EC} = 1/(1-ρ^{EC}) and θ_j are the value shares in non-energy consumption. The structure of final demand is presented in Figure 2.3.

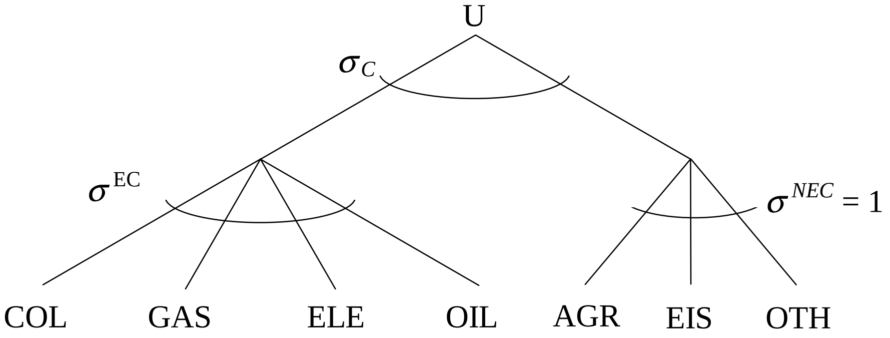

Figure 2.3 Structure of household demand

The indirect utility function that corresponds to Equation (2.22) is:

$$V_r\left(PEC_r, PNEC_r, INC_r\right) = INC_r \cdot \left[\alpha_r^{\sigma^C} PEC_r^{1-\sigma^C} + \beta_r^{\sigma^C} PNEC_r^{1-\sigma^C}\right]^{1/1-\sigma^C} . \tag{2.24}$$

The unit expenditure function e_r (utility price index, PU_r) is then given by e_r = PU_r = $\left[\alpha_r^{\sigma^C} PEC_r^{1-\sigma^C} + \beta_r^{\sigma^C} PNEC_r^{1-\sigma^C}\right]^{1/1-\sigma^C}$. The associated demand functions that have been derived by Roy's identity are:

$$EC_r = \left(\frac{\alpha_r PU_r}{PEC_r}\right)^{\sigma^C} \cdot U \text{ and } NEC_r = \left(\frac{\beta_r PU_r}{PNEC_r}\right)^{\sigma^C} \cdot U , \tag{2.25}$$

where the utility level is given by $U_r = INC_r / PU_r$.

Final demand coefficients ($a_{ir}^C = A_{ir} / U_r$) are:

$$a_{ec,r}^C = \left(\frac{\alpha_r PU_r}{PEC_r}\right)^{\sigma^C} \cdot \left(\frac{\phi_{ec,r} PEC_r}{PA_{ec,r}}\right)^{\sigma^{EC}} \text{ and } a_{nec,r}^C = \left(\frac{\beta_r PU_r}{PNEC_r}\right)^{\sigma^C} \cdot \theta_{nec,r} \cdot \frac{PNEC_r}{PA_{nec,r}}. \quad (2.26)$$

2.3.3 Foreign Trade

All commodities are traded in world markets. Crude oil and coal are imported and exported as homogeneous products with single world prices determined by global demand and supply, 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 substitutability between imports and domestically sold domestic output. Bilateral trade flows are subject to export taxes, tariffs and transportation costs.

On the output side, production of each good may be supplied either to domestic markets (*D*) or export markets (*X*):

$$Y_{ir} = D_{ir} + X_{ir}\,. \quad (2.27)$$

The exports of sector *i* in region *r* are equal to the imports of region *s* from region *r*, M_{irs}, over all trading partners:

$$X_{ir} = \sum_s M_{irs}\,. \quad (2.28)$$

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:

$$A_{ir} = \phi_{ir}\left[\alpha_{ir} D_{ir}^{\rho^D} + \beta_{ir} M_{ir}^{\rho^D}\right]^{1/\rho^D}. \quad (2.29)$$

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

$$M_{ir} = \hat{\phi}_{ir} \left[\sum_s \hat{\alpha}_{isr} X_{isr}^{\rho^M} \right]^{1/\rho^M} \tag{2.30}$$

where X_{isr} is the amount of exports from region s to region r and $\sigma^M = 1/(1 - \rho^M)$ is the Armington elasticity among imported varieties. Typically, elasticities are chosen such that $\sigma^M > \sigma^D$, i.e. imported goods from two different sources are closer substitutes than are aggregate imports and domestic goods. Intermediate as well as final demands are, hence, (nested CES) Armington composites of domestic and imported varieties. Consumers and producers choose between domestically produced goods and imports in response to relative prices. The input coefficients for domestic and imported goods are:

$$a_{ir}^D = \frac{D_{ir}}{A_{ir}} = \phi_{ir}^{\sigma^D - 1} \left[\alpha_{ir} \cdot \frac{PA_{ir}}{PY_{ir}} \right]^{\sigma^D} \quad \text{and} \tag{2.31}$$

$$a_{isr}^M = \frac{M_{isr}}{A_{ir}} = \phi_{ir}^{\sigma^D - 1} \hat{\phi}_{ir}^{\sigma^M - 1} \left[\beta_{ir} \cdot \frac{PA_{ir}}{PM_{ir}} \right]^{\sigma^D} \left[\hat{\beta}_{ir} \cdot \frac{PM_{ir}}{PY_{is}} \right]^{\sigma^M} , \tag{2.32}$$

where the aggregate import price of sector *i* in region *r* is given by:

$$PM_{ir} = \frac{1}{\hat{\phi}_{ir}} \left[\sum_s \hat{\alpha}_{isr}^{\sigma^M} PY_{is}^{1-\sigma^M} \right]^{1/\left(1-\sigma^M\right)} . \tag{2.33}$$

The assumption of product differentiation permits us to match the model with bilateral trade with cross-hauling of trade and avoids unrealistically strong specialization effects in response to exogenous changes in tax policy. Small changes in costs across regions for a given good do not lead to large shifts away from existing trade patterns. On the other hand, the results may then be sensitive to the particular commodity and regional aggregation chosen in the model (Lloyd, 1994).

2.3.4 Carbon Emissions

Greenhouse gases and related gases have direct radiative forcing effects in the atmosphere. The various emissions of 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 contribution to global warming. Carbon emissions are associated with fossil fuel consumption in production, investment, and final demand. Carbon is treated as a Leontief input into production and consumption. Each unit of a fuel emits a known amount of carbon, where different fuels have different carbon intensities. The carbon coefficients that we use 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 of 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 implement 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 economic costs induced by carbon abatement policies represent the resource cost or dead-weight loss to the economy of imposing carbon constraints. 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 substitution, fuel-/non-fuel substitution, and the reduction of intermediate or final consumption. There are no economically feasible end-of-pipe technologies available for carbon abatement.

Given an emission constraint, producers as well as consumers must pay the price of the emissions resulting from the production and consumption processes. Revenues coming from imposing the carbon constraint are given to the representative agent. If we take CO_2 emission restrictions into account, the total cost function that corresponds to the Armington production function in Equation (2.29) is:

$$C_{ir}^{A} = \left[\frac{1}{\phi_{ir}} \left(\alpha_{ir}^{\sigma^D} PY_{ir}^{1-\sigma^D} + \beta_{ir}^{\sigma^D} PM_{ir}^{1-\sigma^D} \right)^{1/\left(1-\sigma^D\right)} + \tau_r \cdot a_i \right] \cdot A_{ir}, \qquad (2.34)$$

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

$$\overline{EMIT}_r = \sum_i a_i \cdot A_{ir}, \qquad (2.35)$$

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

2.3.5 Zero Profit and Market Clearance Conditions

Mathiesen (1985) proposed a representation of an Arrow-Debreu model in which two types of equations define an equilibrium: zero profit conditions and market clearance conditions. The corresponding variables defining an equilibrium are activity levels and commodity prices. The zero profit conditions exhibit complementary with respect to associated activity levels and the market clearance conditions with respect to market prices. The orthogonality symbol, $\perp$, shows the variable that is linked to a certain inequality condition in equilibrium.

Zero profit conditions as derived in Equation (2.2) require that no producer earns a positive profit in equilibrium. The total value of outputs must not exceed the total value of inputs per unit activity. The zero profit conditions for good Y_{ir}, using the variable input coefficient derived above, are:

$$a_{nr}^{K} \cdot PK_r + a_{nr}^{L} \cdot PL_r + \sum_j a_{jnr}^{Y} \cdot PA_{jr} \geq PY_{nr} \qquad \perp Y_{nr} \qquad (2.36)$$

$$a_{vr}^{K} \cdot PK_{r} + a_{vr}^{L} \cdot PL_{r} + a_{vr}^{R} \cdot PR_{vr} + \sum_{j} a_{jvr}^{Y} \cdot PA_{jr} \;\geq\; PY_{vr} \qquad \perp Y_{vr}\,. \qquad (2.37)$$

As an example, the complementarity condition for Equation (2.36) is:

$$\left(a_{nr}^{K} \cdot PK_{r} + a_{nr}^{L} \cdot PL_{r} + \sum_{j} a_{jnr}^{Y} \cdot PA_{jr} - PY_{nr} \right) \cdot Y_{nr} = 0\,. \qquad (2.38)$$

The zero profit conditions for Armington production are:

$$a_{ir}^{D} \cdot PY_{ir} + \sum_{s} a_{isr}^{M} \cdot PY_{is} + a_{i} \cdot \tau_{r} \;\geq\; PA_{ir} \qquad \perp A_{ir}\,. \qquad (2.39)$$

The utility price index (unit expenditure) is:

$$\sum_{i} a_{ir}^{C} \cdot PA_{ir} \;\geq\; PU_{r} \qquad \perp U_{r}\,. \qquad (2.40)$$

The market clearance conditions state that aggregate supply of each good and factor must be at least as great as total intermediate and final demand in equilibrium. The market clearance for good Y_{ir} states that total production is greater than or equal to total demand for domestic production at home and abroad:

$$Y_{ir} \;\geq\; a_{ir}^{D} \cdot A_{ir} + \sum_{s} a_{irs}^{M} \cdot A_{is} \qquad \perp PY_{ir}\,. \qquad (2.41)$$

Markets clearance conditions for the Armington good require that total Armington good supply A_{ir} has to be at least as great as aggregate demand, which consists of intermediate demand, final demand, and investment demand:

$$A_{ir} \;\geq\; \sum_{j} a_{ijr}^{Y} \cdot Y_{jr} + a_{it}^{C} \cdot U_{r} + a_{ir}^{I} \cdot I_{r} \qquad \perp PA_{ir}\,. \qquad (2.42)$$

Primary factor endowments are greater than or equal to primary factor demand:

$$\overline{L}_r \geq \sum_i a_{ir}^L \cdot Y_{ir} \qquad \perp PL_r, \qquad (2.43)$$

$$\overline{K}_r \geq \sum_i a_{ir}^K \cdot Y_{ir} \qquad \perp PK_r, \qquad (2.44)$$

$$\overline{R}_{vr} \geq a_{vr}^R Y_{vr} \qquad \perp PR_{vr}. \qquad (2.45)$$

Total endowment with carbon emission rights is at least as great as total emission demand:

$$\overline{EMIT}_r \geq \sum_i a_i \cdot A_{ir} \qquad \perp \tau_r. \qquad (2.46)$$

The inequality condition for utility is:

$$U_r \cdot PU_r \geq INC_r \qquad \perp PU_r, \qquad (2.47)$$

where the income level INC_r is defined as

$$INC_r = PL_r \cdot \overline{L}_r + PK_r \cdot \overline{K}_r + \sum_v PR_{vr} \cdot \overline{R}_{vr} + TR_r + \overline{B}_r - PI_r \cdot I_r + \overline{EMIT}_r \cdot \tau_r. \qquad (2.48)$$

An equilibrium is characterized by a set of prices and quantities for all goods and factors such that zero profit conditions and market clearance conditions stated above hold.

2.3.6 Data and Calibration

The model is based on a Social Accounting Matrix (SAM), i.e. a comprehensive, economy-wide data framework, 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 et al., 1998). In addition, we use

OECD/IEA energy statistics for 1995 (IEA, 1996). Reconciliation of these data sources yields the benchmark data of our model (see Babiker and Rutherford, 1997). For our model applications, the data set has been aggregated as shown in Table 2.1.

In order to perform simulations with our model, we need 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. First order parameters for the CES production and utility functions are chosen in such a way that the general equilibrium model will have a benchmark equilibrium as its solution. Since we use CES production and utility functions, the assumptions of cost minimization and utility maximization leave us with one free parameter per function. 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 substitution elasticities determine the curvature of isoquants and indifference surfaces, while their position is given by the benchmark equilibrium data. The given set of benchmark quantities and prices, together with the substitution elasticities given in Table 2.2, completely specify the benchmark equilibrium.

Table 2.2 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^{COA}	Coal vs. gas-oil	0.5
Substitution elasticities in final demand		
σ^{C}	Energy vs. non-energy	0.8
σ^{EC}	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
Exogenous supply elasticities of fossil fuels ε		
Crude oil		1.0
Coal		0.5
Natural gas		1.0

For example, consider again the value-added aggregate *KL* in non-fossil fuel production given by Equation (2.8). Deriving the first order conditions for cost minimization and solving for α (where $\beta = 1 - \alpha$) gives:

$$\alpha_{nr} = \frac{PK_{nr} \cdot K_{nr}^{1/\sigma^{KL}}}{PL_{nr} \cdot L_{nr}^{1/\sigma^{KL}} + PK_{nr} \cdot K_{nr}^{1/\sigma^{KL}}} \tag{2.49}$$

where $PL = PL^{*} \cdot (1+tl)$ and $PK = \mathrm{PK}^{*} \cdot (1+tk)$ are the cost of capital and labor including taxes *tl* and *tk*, respectively, and PL^{*} and PK^{*} are the benchmark net-of-tax factor prices. Since benchmark data are given in value terms (incomes, revenues and expenditures), 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 - where there are no distortions (such as taxes) that introduce a wedge between prices for the same good or factor - they have a price of unity in the benchmark (‘Harberger Convention’). Quantities are then defined to be equal to the income, revenue or expenditure concerned. The benchmark net-of-tax factor prices *PL** and *PK** are thus set equal to one and Equation (2.49) can be written as:

$$\alpha_{nr} = \frac{\left(1+tl_{nr}\right)\cdot K_{nr}^{1/\sigma^{KL}} \Big/ \left(1+tk_{nr}\right)\cdot L_{nr}^{1/\sigma^{KL}}}{1+\left(1+tl_{nr}\right)\cdot K_{nr}^{1/\sigma^{KL}} \Big/ \left(1+tk_{nr}\right)\cdot L_{nr}^{1/\sigma^{KL}}} \tag{2.50}$$

Since the unit conventions imply that the number of units of each factor equals the net of tax value of factor use, the values of *L*, *tl*, *K* and *tk* are available for each industry *n* from the underlying input-output tables and α can be calculated according to Equation (2.50) given an exogenous value for the substitution elasticity σ^{KL}. β_{nr} is (1 - α_{nr}). When we know α, β and $\rho = (\sigma - 1)/\sigma$, we can calculate ϕ using the zero-profit condition:

$$PK_{nr}\cdot K_{nr} + PL_{nr}\cdot L_{nr} = KL_{nr}\cdot PKL_{nr} \tag{2.51}$$

and

$$\phi_{nr} = \frac{\left(1+tk_{nr}\right)\cdot K_{nr} + \left(1+tl_{nr}\right)\cdot L_{nr}}{\left[\alpha_{nr}K_{nr}^{\rho^{KL}} + \beta_{nr}L_{nr}^{\rho^{KL}}\right]^{1/\rho^{KL}}}. \tag{2.52}$$

In a second step, we do a 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 Business-as-Usual 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 (1995b, 1999) within the General Algebraic Modeling System (GAMS) mathematical modeling language (Brooke et al., 1996). The complementarity problem is solved in GAMS using the PATH solver (Ferris and Munson, 2000).

2.4 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 costs and the total 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 parameterization 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.[9]

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 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

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[9] Chapter 5 and Chapter 6 analyze in more detail the implications of cross-border investments by industrialized countries in developing countries in order to achieve their reduction obligation.

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], and oil price responses [OIL]:

[ARMINGTON] As described in Section 2.3, 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.

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 2.12 to 2.33 below, summarizing the results of our sensitivity analysis.[10]

2.4.1 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 projections for gross domestic product, fuel prices, energy efficiency improvements etc. As outlined in Section 2.3, 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 2.3 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] Other OECD (OOE), i.e. Australia and New Zealand, is allowed to increase emissions under the Kyoto Protocol slightly 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.

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[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.

Table 2.3 Nominal and effective CO_2 reduction requirements (in %)

Region		Nominal reduction (wrt 1990)	Effective reduction (wrt 2010)
CEA	Central European Associates	7.00	–4.21
EUR	Europe (EU15 and EFTA)	7.73	16.60
FSU	Former Soviet Union	0.00	–31.74
JPN	Japan	6.00	23.05
OOE	Other OECD (Australia and New Zealand)	0.91	22.68
USA	United States	7.00	33.19

2.4.2 NOTRADE: Domestic Abatement Policies

2.4.2.1 Marginal abatement costs and welfare impacts

Table 2.4 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 2.4 reveals that the relative cutback requirements are only one determinant of marginal abatement costs.

Table 2.4 Marginal abatement costs and welfare effects

Region		Marginal abatement cost [a]	Welfare effect [b]
CEA	Central European Associates	0	0.29
EUR	Europe (EU15 and EFTA)	113	–0.18
FSU	Former Soviet Union	0	–0.25
JPN	Japan	229	–0.32
OOE	Other OECD	107	–0.66
USA	United States	160	–0.60
ASI	Other Asia (except for China and India)	-	0.03
CHN	China (including Hong Kong and Taiwan)	-	0.22
IND	India	-	0.20
MPC	Mexico and OPEC	-	–0.48
ROW	Rest of World	-	–0.06

[a] $US95 per ton of carbon
[b] in % change of real consumption as compared to BaU

The latter depend also on the BaU energy price levels. 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.

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[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.

2.4.2.2 Welfare effects

The static welfare impacts are measured as the percentage change in real consumption with respect to BaU, which is equivalent to percentage Hicksian equivalent variations in income because our utility function is linearly homogeneous.[13] 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. 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]

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[13] The choice of the appropriate welfare measure for a particular model is a key issue for model based economic analysis. To measure the overall impact of climate change policies on national economic welfare, alternative macroeconomic variables besides real consumption and equivalent variation have been used in different studies, e.g. gross domestic product (GDP) (Manne and Richels, 1999) or gross national product (GNP) (Tulpulé et al., 1999). Weitzman (1976) shows that the net national product (NNP), i.e. the sum of a nations's consumption and net investment, is in theory a proxy for the discounted value of future consumption. Hence, GNP or GDP are conceptually more appropriate welfare measures than consumption in a static model. However, since investment is kept fixed in our model we adhere to consumption to evaluate the impacts of policy changes.

[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).

Table 2.4 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 2.4. Given our core model parameterization, 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 2.4, 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.

2.4.2.3 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 2.5 and 2.6 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-

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[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.

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 2.6, the EU exports to FSU drop by nearly 10%, whereas imports from FSU to EU increase by roughly 9%.

Table 2.5 Impacts on energy-intensive production (% change)

Region		
CEA	Central European Associates	1.93
EUR	Europe (EU15 and EFTA)	–0.53
FSU	Former Soviet Union	4.87
JPN	Japan	–0.82
OOE	Other OECD (Australia and New Zealand)	–1.33
USA	United States	–2.33
ASI	Other Asia (except for China and India)	1.47
CHN	China (including Hong Kong and Taiwan)	2.08
IND	India	2.24
MPC	Mexico and OPEC	3.50
ROW	Rest of World	1.17

Table 2.6 Trade in energy-intensive production (% change)

Imports from Row region to Column region	CEA	EUR	FSU	JPN	OOE	USA
CEA	1.51	3.59	–5.69	6.34	5.96	8.67
EUR	–2.36	–0.36	–9.88	2.29	1.91	4.56
FSU	6.77	8.89	–1.14	11.81	11.31	14.19
JPN	–3.54	–1.59	–11.04	0.82	0.58	3.17
OOE	–6.11	–4.29	–13.57	–1.69	–1.99	0.37
USA	–5.69	–3.79	–13.15	–1.23	–1.71	–2.33
ASI	1.24	3.35	–6.38	6.11	5.67	8.42
CHN	2.31	4.37	–5.42	7.13	6.71	9.46
IND	3.38	5.45	–4.38	8.23	7.82	10.61
MPC	2.45	4.52	–5.29	7.27	6.83	9.59
ROW	0.85	2.90	–6.83	5.57	5.25	7.97

Table 2.6 continued

Imports from Row region to Column region	ASI	CHN	IND	MPC	ROW
CEA	1.58	–0.22	–1.96	0.75	0.67
EUR	–2.28	–4.03	–5.62	–3.08	–3.14
FSU	6.72	4.86	3.33	5.88	5.80
JPN	–3.45	–5.12	–6.66	–4.27	–4.39
OOE	–6.10	–7.71	–9.28	–6.86	–6.93
USA	–5.59	–7.23	–8.64	–6.44	–6.39
ASI	1.32	–0.44	–2.08	0.53	0.43
CHN	2.34	0.54	–1.11	1.53	1.44
IND	3.39	1.59	2.24	2.58	2.50
MPC	2.47	0.66	–1.02	1.64	1.59
ROW	0.86	–0.92	–2.49	0.08	0.01

2.4.2.4 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).

Table 2.7 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.

Table 2.7 Leakage rates (in %)

Region		Leakage rate
ASI	Other Asia (except for China and India)	0.97
CHN	China (including Hong Kong and Taiwan)	14.15
IND	India	2.40
MPC	Mexico and OPEC	1.55
ROW	Rest of World	2.82
TOTAL		21.90

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 2.4.3) or the substitutability between imported and domestic production (see Section 2.4.7).

2.4.3 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.

Emissions trading 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).

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

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[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.

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 2.4.5). Tables 2.8 and 2.9 summarize the changes in marginal costs and welfare levels when we move from NOTRADE to policies which allow for trade in permits among Annex B countries (ANNEXB) or all world regions (GLOBAL).

Table 2.8 Marginal abatement costs (in $US95 per ton of carbon)

Region	NOTRADE	ANNEXB	GLOBAL
CEA	0	57	31
EUR	113	57	31
FSU	0	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 2.9 Welfare impacts (% 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.

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 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.

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[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.

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 (Table 2.10). 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 (Table 2.11). 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.

Table 2.10 Leakage rates (in %)

Region		NOTRADE	ANNEXB
ASI	Other Asia (except for China & India)	0.97	0.71
CHN	China	14.15	9.85
IND	India	2.40	1.70
MPC	Mexico and OPEC	1.55	1.15
ROW	Rest of World	2.82	2.39
TOTAL		21.90	15.79

Table 2.11 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

2.4.4 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 2.12 through 2.15 summarize the economic and environmental implications of this scenario.[18]

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

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[18] The economic and environmental implications of the US withdrawal from the Kyoto Protocol are discussed in more detail in Chapter 4 using a partial equilibrium model of the permit market.

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 2.12 Welfare impacts (% change of real consumption)

Region		REF	NOUSA
CEA	Central European Associates	0.29	0.16
EUR	Europe (EU15 and EFTA)	–0.18	–0.22
FSU	Former Soviet Union	–0.25	–0.46
JPN	Japan	–0.32	–0.36
OOE	Other OECD (Australia & New Zealand)	–0.66	–0.44
USA	United States	–0.60	0.01
ASI	Other Asia (except for China and India)	0.03	–0.02
CHN	China (incl. Hong Kong and Taiwan)	0.22	0.03
IND	India	0.20	0.04
MPC	Mexico and OPEC	–0.48	–0.15
ROW	Rest of World	–0.06	–0.03
TOTAL		–0.29	–0.14

Table 2.13 Marginal abatement costs (in $US95 per ton of carbon)

Region		REF	NOUSA
CEA	Central European Associates	0	0
EUR	Europe (EU15 and EFTA)	113	107
FSU	Former Soviet Union	0	0
JPN	Japan	229	224
OOE	Other OECD (Australia and New Zealand)	107	98
USA	United States	160	-
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	-	-

Table 2.14 Carbon emissions (in Gt)

Region		REF	NOUSA
CEA	Central European Associates	0.26	0.26
EUR	Europe (EU15 and EFTA)	1.01	1.01
FSU	Former Soviet Union	0.94	0.90
JPN	Japan	0.34	0.34
OOE	Other OECD (Australia and New Zealand)	0.22	0.22
USA	United States	1.41	2.14
ASI	Other Asia (except for China and India)	0.37	0.37
CHN	China (incl. Hong Kong and Taiwan)	1.62	1.51
IND	India	0.36	0.34
MPC	Mexico and OPEC	0.65	0.64
ROW	Rest of World	0.70	0.68
TOTAL		7.88	8.41

Table 2.15 Leakage rates (in %)

Region		REF	NOUSA
USA	United States	0.00	10.28
ASI	Other Asia (except for China and India)	0.97	0.88
CHN	China (incl. Hong Kong and Taiwan)	14.15	10.77
IND	India	2.40	1.83
MPC	Mexico and OPEC	1.55	1.54
ROW	Rest of World	2.82	2.83
TOTAL		21.90	28.13

2.4.5 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 mitigation 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. Moreover, investments in abatement projects - especially CDM projects in developing countries - are risky. 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. The implications of investment risks in project-based emission crediting are analyzed in detail in Chapter 6 using a partial equilibrium model of the permit market.

Closely linked to the risk problem is the issue of transaction costs since risks are sometimes considered as transaction costs in a broader use that covers any policy-related costs other than the conventionally measured economic adjustment responses (Krutilla, 1999). Transaction costs may arise from a variety of activities associated with market exchange. Examples are search and information acquisition or negotiation, monitoring and enforcement of contracts (Stavins, 1995). Model simulations that neglect the existence of transaction costs overestimate the potential benefit from the international trade of emission permits.

These considerations show the need to assess the effects of transaction costs. Transaction costs might be significant especially for (small) CDM projects.[19] 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.[20]

Tables 2.16–2.18 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.[21]

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[19] Transaction costs may range from 0.1 €/tCO_2 for very large projects with more than 200,000 tCO_2/year reduction such as large hydro, gas power plants, and large-scale afforestation up to 1,000 €/tCO_2 for micro projects with less than 200 tCO_2/year reduction, e.g. photovoltaic projects (Michaelowa et al., 2002).

[20] 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.

[21] Remember that the larger part of potential efficiency gains from trading is due to sales from FSU and CEA – see Section 2.4.3.

Table 2.16 Welfare impact (% 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 2.17 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

Table 2.18 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

2.4.6 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.

Our sensitivity analysis below illustrates the importance of baseline assumptions, which generally receive little attention in the literature. Based on projections by the US Department of Energy 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 2.19 reports the increase in the effective cut-back requirements of Annex B countries as compared to the reference case (carbon emissions are given in Table 2.24).

Table 2.19 Effective CO_2 emission cut-back requirements under BASELINE (in % with respect to 2010)

Region		REF	HI
CEA	Central European Associates	–4.21	1.19
EUR	Europe (EU15 and EFTA)	16.60	21.03
FSU	Former Soviet Union	–31.74	–28.78
JPN	Japan	23.05	27.33
OOE	Other OECD (Australia & New Zealand)	22.68	26.40
USA	United States	33.19	33.48

The increase in projected BaU emissions and effective cutback requirements causes a steep rise in marginal abatement costs and welfare losses (Tables 2.20 and 2.21).

Table 2.20 Welfare impacts (% change of real consumption)

Region		REF	HI
CEA	Central European Associates	0.29	0.48
EUR	Europe (EU15 and EFTA)	–0.18	–0.46
FSU	Former Soviet Union	–0.25	–0.53
JPN	Japan	–0.32	–0.63
OOE	Other OECD (Australia and New Zealand)	–0.66	–1.09
USA	United States	–0.60	–0.76
ASI	Other Asia (except for China and India)	0.03	0.08
CHN	China (including Hong Kong and Taiwan)	0.22	0.31
IND	India	0.20	0.32
MPC	Mexico and OPEC	–0.48	–0.77
ROW	Rest of World	–0.06	–0.11
TOTAL	–	0.29	–0.49

Table 2.21 Marginal abatement costs (in $US95 per ton of carbon)

Region		REF	HI
CEA	Central European Associates	0	14
EUR	Europe (EU15 and EFTA)	113	204
FSU	Former Soviet Union	0	0
JPN	Japan	229	379
OOE	Other OECD (Australia & New Zealand)	107	167
USA	United States	160	207
ASI	Other Asia (except for China & India)	-	-
CHN	China (including Hong Kong & Taiwan)	-	-
IND	India	-	-
MPC	Mexico and OPEC	-	-
ROW	Rest of World	-	-

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 2.22) and a higher leakage rate of sub-global action as compared to the reference case (Table 2.23).

Table 2.22 Energy-intensive production (% change)

Region		REF	HI
CEA	Central European Associates	1.93	2.07
EUR	Europe (EU15 and EFTA)	–0.53	–1.22
FSU	Former Soviet Union	4.87	6.95
JPN	Japan	–0.82	–1.37
OOE	Other OECD (Australia & New Zealand)	–1.33	–2.89
USA	United States	–2.33	–3.03
ASI	Other Asia (except for China & India)	1.47	2.41
CHN	China (including Hong Kong & Taiwan)	2.08	3.05
IND	India	2.24	3.21
MPC	Mexico and OPEC	3.50	6.22
ROW	Rest of World	1.17	1.98

Table 2.23 Leakage rates (in %)

Region		REF	HI
ASI	Other Asia (except for China & India)	0.97	1.31
CHN	China (including Hong Kong & Taiwan)	14.15	17.40
IND	India	2.40	2.76
MPC	Mexico and OPEC	1.55	2.35
ROW	Rest of World	2.82	3.48
TOTAL		21.90	27.29

Table 2.24 Carbon emissions (in Gt)

Region		REF	HI
CEA	Central European Associates	0.26	0.27
EUR	Europe (EU15 and EFTA)	1.01	1.01
FSU	Former Soviet Union	0.94	0.97
JPN	Japan	0.34	0.34
OOE	Other OECD (Australia & New Zealand)	0.22	0.22
USA	United States	1.41	1.41
ASI	Other Asia (except for China & India)	0.37	0.45
CHN	China (including Hong Kong & Taiwan)	1.62	2.02
IND	India	0.36	0.42
MPC	Mexico and OPEC	0.65	0.76
ROW	Rest of World	0.70	0.84
TOTAL		7.88	8.70

2.4.7 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 2.25). 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 2.26). 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.

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 2.27) which causes an increase in the global leakage rate (Table 2.28).

Table 2.25 Marginal abatement costs (in $US95 per ton of carbon)

Region	LOARM	REF	HIARM
CEA	0	0	0
EUR	121	113	108
FSU	0	0	0
JPN	255	229	216
OOE	114	107	102
USA	161	160	158
ASI	-	-	-
CHN	-	-	-
IND	-	-	-
MPC	-	-	-
ROW	-	-	-

Table 2.26 Welfare impacts (% 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

Table 2.27 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

Table 2.28 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

2.4.8 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). Tables 2.29–2.33 report the economic implications of changes in the responsiveness of crude oil prices.

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.

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.[22] As expected, leakage through adjustments in international oil markets declines with higher oil supply elasticities. However, the induced changes are rather small.

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[22] The implications of changes in coal supply elasticities are analogous. For the sake of brevity, the respective results are omitted here.

Table 2.29 Welfare impacts (% 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

Table 2.30 Marginal abatement costs (in $US95 per ton of carbon)

Region	LO_OIL	REF	HI_OIL
CEA	0	0	0
EUR	114	113	112
FSU	0	0	0
JPN	231	229	228
OOE	108	107	106
USA	161	160	159
ASI	-	-	-
CHN	-	-	-
IND	-	-	-
MPC	-	-	-
ROW	-	-	-

Table 2.31 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

Table 2.32 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

Table 2.33 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

2.5 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, quantitative 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 reader, who needs to be familiar with not only one but various models, including the respective differences in parameterization, 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 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:

(i) 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 translate 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.

(ii) 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.

(iii) 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.

(iv) The drop in international fuel prices and changes in the pattern of trade for energy-intensive goods induce 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.

(v) 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.

(vi) 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 less 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.

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.

3 Environmental Taxes under Imperfect Competition [*]

3.1 Introduction

The theory of environmental policy has recommended emission taxes for decades, on the grounds that they provide a cost-effective means of environmental regulation. In view of the need to combat global warming and the relative ease of designing an appropriate tax scheme for CO_2 as the most important greenhouse gas, environmental taxes have recently become popular in the political arena, too.

Environmental taxation has effects both at the sectoral and the macroeconomic level. The sectoral effect, i.e. induced structural change, is important not only *per se*, but also because it is a key determinant of the macroeconomic consequences.

The structural changes induced by environmental taxation are usually analyzed in a conventional perfect-competition factor-endowment framework. As the imposition of an environmental tax on emissions increases the price of the factor ‘environment’, the production of the ‘dirty’ goods, which use the environment intensively, will decrease, and that of the environmentally friendly, i.e., capital/labor intensive goods will increase. In an open economy, the tax-induced changes in the cost structure imply changes in comparative advantage and lead to an adjustment of international specialization patterns. Papers which examine international aspects of environmental policy in such a framework include Felder and Rutherford (1991), Oliveira-Martins, Burniaux and Martin (1992), Pezzey (1992), Manne

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[*] This chapter is based on the paper ‘Environmental Taxation and Structural Change in an Open Economy - A CGE Analysis with Imperfect Competition and Free Entry’, with C. Böhringer and H. Welsch, *ZEW Discussion Paper* 01-07, Mannheim, and *University of Oldenburg Discussion Paper* V-215-01, Oldenburg, 2001.

and Oliveira-Martins (1994), Welsch (1996a), Conrad and Schmidt (1998), Bernstein et al. (1999).[23]

In contrast to the perfect-competition approach to environmental taxation in open economies, recent modeling of trade policy emphasizes the importance of imperfect competition and economies of scale (see, e.g., Smith and Venables, 1988; Delorme and van der Mensbrugghe, 1990; Norman, 1990; Willenbockel, 1994; Harrison et al., 1996). The standard framework currently adopted in modeling trade policy involves imperfect competition due to fixed costs, and a variable number of firms due to free entry/exit. Free entry/exit joined with fixed costs is the natural assumption to be made in order to explain the number of firms, unless imperfect competition is the result of regulation. In such a setting, the effect of policy measures (like, e.g., trade liberalization) works largely through their effect on the number and size of firms and the associated changes in economies of scale.

This chapter shows that changes in economies of scale are important also when the effects of environmental taxation are to be examined. Using a multi-sector open economy computable general equilibrium model for Germany we find that the degree of structural change induced by a carbon tax is substantially larger under imperfect competition than under perfect competition. The logic behind this result is that the carbon tax, by changing comparative advantage, leads to a shift in the demand structure facing the various industries and, hence, to a shift in their overall demand elasticities. The elasticity of demand is typically higher for sales abroad than for sales in domestic markets. The reason is that unlike the elasticity on the export market, the elasticity on the domestic market is derived from production and consumption elasticities which are typically less than one (see, e.g., Burniaux et al., 1992). Therefore, industries which gain in comparative advantage - and hence sell a larger portion of their output abroad - are facing a higher overall demand elasticity. This reduces market power, drives firms out of the market, and raises economies of scale. The reverse applies to industries which lose in comparative advantage: Their demand elasticity drops, and economies of scale get reduced. As a result, the change in relative costs across industries is enhanced, and so is induced structural change. At the macroeconomic level, the costs to the German economy of environmental regulation turn out to be higher under

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[23] For a review of the perfect-competition factor endowment approach to environmental taxation and trade as well as of simulation results obtained in this framework see Klepper (1998).

imperfect than under perfect competition, because on the whole the changes in economies of scale across imperfectly competitive sectors are negative.

Despite the potential importance of imperfect competition for induced structural change, environmental economics has mostly addressed market structure in a partial-equilibrium framework (see, e.g., the contributions in Carraro et al., 1996), which, by definition, does not allow the analysis of structural change. An environmentally-oriented computable general equilibrium model with imperfect competition on goods markets is presented by Conrad and Wang (1993), but in this model, as in the partial equilibrium models, firm numbers and scale economies are fixed.

The chapter is organized as follows. Section 3.2 provides a non-technical overview of our analytical framework. Section 3.3 presents the simulation results and their economic interpretation. Section 3.4 summarizes and concludes.

3.2 The Model

3.2.1 General Framework

This section presents the main characteristics of an extended version of our comparative static multi-sector computable general equilibrium (CGE) model (see Section 2.3) for the German economy. It is designed to assess the medium-run effects of carbon/environmental taxes on trade and industrial structure (see Appendix 3.A for an algebraic model formulation). The analysis covers 13 sectors and 3 primary factors as described in Table 3.1. The sectoral aggregation captures key dimensions in the analysis of greenhouse gas abatement, such as differences in carbon intensities and the degree of substitutability across energy goods and carbon-intensive non-energy goods. The energy goods identified in the model are hard coal (HCO), lignite (SCO), crude and refined oil (OIL), natural and manufactured gases (GAS) and electricity and steam (ELE). The non-energy sectors include important carbon-intensive and energy-intensive industries that are potentially most affected by carbon abatement policies, such as basic materials and chemical products (MMC), investment goods (EQP) and transport (TRN). The rest of the economy is divided into agricultural production (AGR), consumption goods (CSG), construction (CST), private services (SER) and public services

(PUB). Primary factors include labor (LAB), capital (CAP) and fossil-fuel resources (RES). Labor and capital are treated as perfectly mobile across sectors whereas fossil-fuel resources are sector-specific. Factor markets are treated as perfectly competitive.

Table 3.1 Sectors and primary factors in the general equilibrium model for Germany

Commodities				Primary factors	
AGR	Agricultural goods			CAP	Capital
MMC	Basic materials / chemical products			LAB	Labor
EQP	Investment goods			RES	Sector-specific resource
CSG	Consumption goods				
CST	Construction				
TRN	Transport				
SER	Private services				
PUB	Public services				
HCO	Hard coal	FOS	Fossil fuels		
SCO	Lignite				
OIL	Crude oil and refined oil products				
GAS	Natural and manufactured gases				
ELE	Electricity and steam				

Nested constant elasticity of substitution (CES) cost functions are employed to specify the substitution possibilities in domestic production between capital, labor, energy and material (non-energy) intermediate inputs. Output in production sectors other than fossil fuels and electricity is produced with fixed-coefficient (Leontief) inputs of intermediate non-energy goods and an aggregate of energy and a value added composite. The value-added composite consists of a CES aggregation of capital and labor. The energy aggregate is, in turn, produced with a CES function of electricity and a composite of primary energy inputs. The primary energy composite is then defined as a CES function of a CES aggregate of hard coal and lignite and a CES aggregate of refined oil and natural gas. In the production of electricity, the primary energy composite is defined as a CES function of oil and an aggregate of coal and gas. The coal-gas composite is a CES function of gas and a CES aggregate of hard coal and lignite. In the production of fossil fuels, labor, capital and fossil fuel inputs are aggregated in fixed proportions at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with exogenously given price elasticities of fossil fuel supplies.

Private demand for goods and services is derived from utility maximization of a representative household subject to a budget constraint. Total income of the representative household consists of factor income and transfers. Utility is derived from real consumption and savings. The top level of the utility function is specified as a Cobb-Douglas function resulting in a constant savings rate. Real consumption of the representative agent is a CES composite of an energy aggregate and a Cobb-Douglas non-energy composite. The energy composite is defined as a CES function of electricity and the primary energy composite. The primary energy composite is given as a CES function of hard coal, lignite and a CES aggregate of oil and gas. Government demand is fixed exogenously Total investment demand equals savings; the investment good is a Cobb-Douglas aggregate of intermediate inputs.

All goods are traded internationally. According to Armington (1969), foreign trade modeling involves international product differentiation in the sense that imported and domestically produced goods of the same kind are treated as incomplete substitutes. For each product variety (Armington aggregate) the substitution possibility between the domestically produced good and the world import good is described by a CES function. The world import goods, in turn, are given as a CES aggregate of exports from Germany and exports from the rest of the world (ROW). The ROW closure requires that the value of imports to ROW are equal to the value of exports from ROW after including a constant benchmark trade surplus (deficit). Exports from ROW are determined by an export supply function. An endogenous exchange rate assures that demand equals supply for ROW exports.

3.2.2 Market Structure

Within the general framework described in Section 3.2.1, each sector can deliberately be modeled as being perfectly or imperfectly competitive. We assume that imperfect competition, if present, is due to fixed costs, not to regulation of entry. Entry or exit and, hence, the number of firms in an industry are determined by the usual zero-profit condition.[24]

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[24] Recall that our analysis refers to the medium term. Therefore, free entry/exit is a sensible assumption in the absence of entry regulation.

There are several ways in which imperfect competition can be specified. In the case of monopolistic competition (Krugman, 1979), there are several incompletely substitutable varieties of each good, and each firm in a particular industry supplies exactly one variety. Since the elasticity of substitution is the same for all pairs of varieties, there is no differentiation between domestic and foreign suppliers.

In contrast to this assumption, we choose a set-up in which varieties from the same country of origin are closer substitutes for each other than are varieties from different countries. This is in the spirit of Armington (1969), who introduced the theory of demand for goods distinguished by place of production. More specifically, we assume that all domestic varieties are perfect substitutes for each other, as are all foreign varieties, but that domestic and foreign varieties are incomplete substitutes. This specification avoids the difficulty of selecting intra-country elasticities of substitution; the inter-country (Armington) elasticities are available from econometric estimation or literature search (see Appendix 3.C).

Within this general framework, each imperfectly competitive sector *j* is modeled as a homogenous Cournot-Oligopoly, in which the market demand facing the suppliers reflects the fact that their supply competes with imperfect substitutes from abroad. Profit-maximizing behavior then entails the equalization of marginal cost and perceived marginal revenue, which implies that the output price (P_j) is a markup on marginal cost (MC_j):

$$P_j = \frac{MC_j}{1 - \frac{1}{N_j \cdot \eta_j}}, \tag{3.1}$$

where η_j is the price elasticity of market demand and N_j the number of firms in the sector. Evidently, the markup rate is a decreasing function of both the price elasticity and the number of firms. Both of these determinants of the markup rate are variable in our framework. They will be considered subsequently.

The price elasticity of market demand involves the various demand categories at the different market stages. In the domestic market, output Y_j of the good *j* competes with imports M_j of the world import good. Both form the Armington aggregate A_j. Dropping the commodity/sector subscript, the demand for the domestic good can thus be written as

$$Y = F(P) \cdot A, \tag{3.2}$$

where $F(P)$ captures the effect of output price P on demand at any given level of the Armington good A. Since A also depends on P, the demand elasticity $\eta \equiv -(\partial Y / \partial P)/(Y / P)$ can be decomposed in the following way

$$\eta = \eta_F + \eta_A, \tag{3.3}$$

where $\eta_F \equiv -(\partial F / \partial P)/(F / P)$ and $\eta_A \equiv -(\partial A / \partial P)/(A / P)$.

With respect to η_A, it has to be observed that the demand for the Armington good A is the sum of several demand categories: intermediate demand from the various production sectors, consumption demand, investment demand, and export demand. For convenience, the exposition distinguishes only between domestic demand D (intermediate, consumption, and investment demand) and export demand X, with corresponding demand elasticities η_D and η_X. The elasticity of the demand for A then is the weighted average of η_D and η_X, and Equation (3.3) can therefore be rewritten as

$$\eta = \eta_F + \frac{D}{A}\eta_D + \frac{X}{A}\eta_X, \tag{3.4}$$

The price elasticity of domestic demand, η_D, is in a complex way composed of substitution elasticities which characterize production and utility functions. These substitution elasticities are less than one (see Appendix 3.C) and so is the price elasticity of domestic demand. By contrast, the price elasticity of export demand, η_X, is typically larger.[25] As environmental taxes lead to a shift in comparative advantage, the D/A and X/A ratios change, implying a rise or fall in the price elasticity of demand: an increased (decreased) share of exports in total sales results in a higher (lower) price elasticity of the good.[26] In this sense, increasing export orientation reduces market power.

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[25] The precise forms of η_X and η_F are stated in Appendix 3.B.

[26] The partial elasticities in Equation (3.4) involve fixed elasticities of substitution and variable value shares. The latter are also affected by environmental taxes, but to a lesser extent than the quantity shares *D/A* and *X/A*. The statement made in the text is not affected by changes in the value shares.

Given the assumption of free entry and exit, changes in the price elasticity have implications for the size and number of firms in an industry: Under free entry and exit, prices are not only linked to marginal costs via the markup equation (3.1); they also equal average costs due to the zero-profit condition. When the price elasticity changes, reconciliation of the two conditions requires that the size of the firms adjusts, as illustrated in Figure 3.1. If the elasticity of market demand rises, the markup drops and firms are driven out of the market. Markup revenues do no longer make up for fixed costs inducing firm exit until the zero profit condition is restored. Since average costs are decreasing in output levels (due to fixed costs), economies of scale become effective, and both average costs and prices fall. The reverse happens if the quantity shares change in such a way that the overall demand elasticity gets reduced. These changes in economies of scale enhance the structural change caused by environmental taxation.

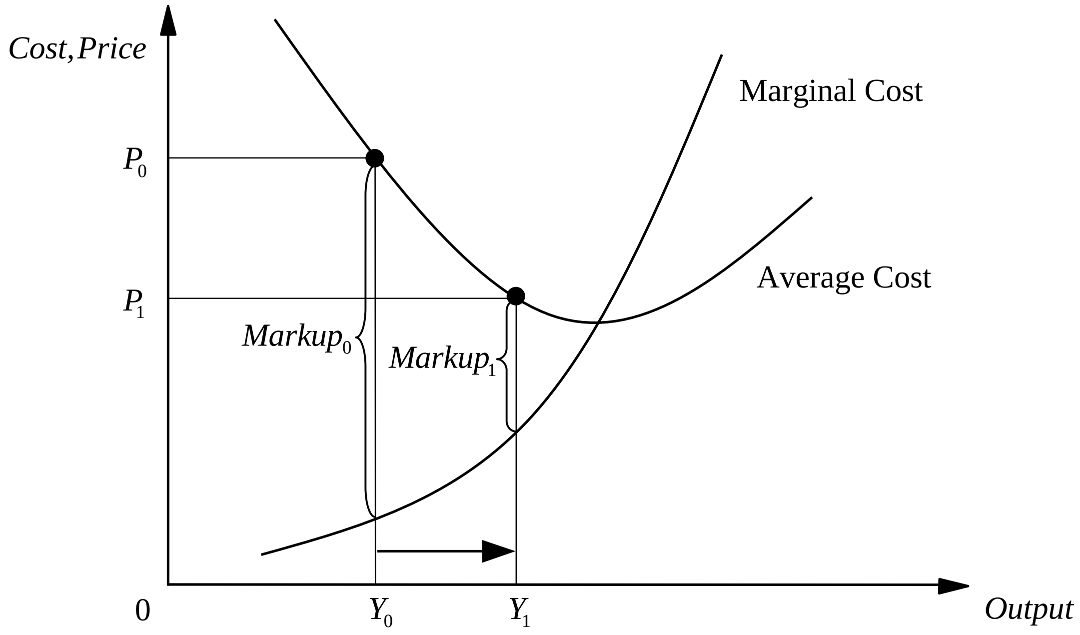

Figure 3.1 Cost curves under imperfect competition due to fixed costs

3.2.3 Data and Parameterization

Benchmark data are used to calibrate parameters of the functional forms from a given set of quantities, prices and elasticities. Data from two different sources are combined to yield a consistent benchmark data set for 1995:

- EUROSTAT Input-Output-Table for Germany with 25 sectors (Beutel, 1999; EUROSTAT, 1999).
- IEA energy balances and energy prices/taxes (IEA, 1999). IEA provides statistics on physical energy flows and energy prices for industrial and household demands.

The information from IEA energy balances and energy prices is used to split up the aggregate energy sector, as given in EUROSTAT's input-output table for Germany, into the 5 energy sectors described above. Our choice of elasticities is mostly based on reviews of the relevant literature (see, e.g. Burniaux et al., 1992). The Armington elasticities between domestic output and imports have been estimated on time series data from the 'NEW CRONOS' databank of EUROSTAT (for details, see Böhringer et al., 2000b).

Estimates of markup rates in various industries can be found in Capros et al. (1997). These estimates suggest that, in terms of our sectoral classification, imperfect competition should be taken to prevail in the sectors ‘basic materials and chemicals’ (MMC) and ‘investment goods’ (EQP). The markup rates determine the share of fixed costs in total costs. Fixed costs are treated as part of capital costs. Appendix 3.C provides a summary of key elasticities and the markup rates employed for our simulations.

3.3 Simulation Results

Our simulations refer to a uniform tax on carbon dioxide that is unilaterally introduced in Germany to achieve the country's declared target of reducing its carbon emissions until 2005 by 25 percent as compared to 1990 emission levels (Bundesregierung, 2000). Since BaU emissions in 2005 are projected to be 14 percent below 1990 levels (see European Commission, 1999a), this target implies an effective abatement requirement of 11 percent below BaU. The revenue from the carbon tax is redistributed to private households in a lump-sum fashion.

With respect to market structure, our core simulation entails imperfect competition (IC) in the sectors MMC and EQP, in agreement with the evidence mentioned in Section 3.2.3. In order to see how the results depend on the market structure, we contrast the IC case with alternative scenarios in which all industries are perfectly competitive (PC) or imperfect competition prevails only in MMC or EQP (scenarios IC_MMC and IC_EQP). We first consider the PC scenario, because the effects arising in this case provide the background against which the structural changes under IC are to be interpreted.

3.3.1 Sectoral Effects under Perfect Competition

As a result of the carbon tax, the suppliers of fossil fuels and the electricity industry are facing a substantial decline in output (see Table 3.2). Other negatively affected sectors are agriculture, basic materials and transport, all of them rather energy intensive. On the other hand, consumption goods, construction, and private and public services experience a small increase; the investment goods industry has a rather significant expansion of output.

These effects are determined by the various industries' factor intensities (see Appendix 3.C). Especially, sectors with a high energy/labor ratio (AGR, FOS, ELE, MMC, TRN) are losers of structural change, whereas those with a low energy/labor ratio (EQP, CST, SER, PUB) benefit from the change in the ratio of wages to energy costs. These relationships are consistent with standard perfect-competition factor-endowment models in which the imposition of a tax on emissions increases the price of the factor ‘environment’. Previous simulation studies in perfect competition settings have typically been in line with this logic and produced results very similar to ours: Basic industries of outward oriented economies experience losses, whereas other manufacturing sectors tend to gain.[27]

On the international level, these changes in the cost structure translate into changes in comparative advantage. As shown in Table 3.3, any increase (or decrease) in output goes along with an increase (decrease) in exports. Note that the changes in exports are more pronounced than the corresponding changes in output. For instance, exports of investment goods rise by 3 percent, whereas total output increases not more than 1.4 percent. Exports of basic materials and chemicals, conversely, drop by almost 10 percent, whereas output drops by only about 3.6 percent. The reason for these results is that the price elasticity of export demand is larger than the price elasticity of the various categories of domestic demand.

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[27] See Klepper (1998) for a review.

Table 3.2 Change in output (% change)

	PC	IC_MMC	IC_EQP	IC
AGR	-0.56	-0.49	-0.61	-0.56
FOS	-14.17	-14.14	-14.18	-14.15
ELE	-6.89	-7.05	-6.88	-7.05
MMC	-3.64	-5.19	-3.77	-5.45
EQP	1.36	1.60	1.69	2.06
CSG	0.13	0.22	0.07	0.14
CST	0.35	0.31	0.35	0.31
TRN	-4.19	-4.03	-4.35	-4.23
SER	0.08	0.03	0.11	0.06
PUB	0.03	0.02	0.03	0.01

Table 3.3 Change in exports (% change)

	PC	IC_MMC	IC_EQP	IC
AGR	-4.47	-4.02	-4.68	-4.31
FOS	-29.21	-28.93	-29.28	-29.01
ELE	-46.40	-45.56	-46.53	-45.70
MMC	-9.69	-13.69	-10.15	-14.54
EQP	3.01	3.78	3.71	4.78
CSG	0.42	1.10	0.02	0.59
CST	2.18	3.25	1.58	2.49
TRN	-14.68	-13.11	-15.46	-14.04
SER	6.62	7.73	6.27	7.27
PUB	6.99	8.92	5.89	7.58

3.3.2 Sectoral Effects under Imperfect Competition

As discussed above, environmental taxes lead to a shift in comparative advantage. This is true irrespective of the market structure. Under imperfect competition, however, the change in comparative advantage has implications for market structure: With free entry and exit, the number of firms in a particular industry is inversely related to the price elasticity of market demand. A gain in an industry's comparative advantage leads to a shift in sales from the domestic markets to the export markets. Given that the price elasticity of export demand is larger than the price elasticity of domestic demand, this implies a rising overall price elasticity, with an increase in scale economies. The reverse happens if an industry faces a loss in comparative advantage.

The outcome from these effects is shown in Table 3.4 and Table 3.5. It can be seen that under IC, the demand elasticity in the basic materials/chemicals industry drops by almost 7.1 percent and scale economies (defined as output per firm) drop by almost 7.3 percent. In the investment goods sector the demand elasticity rises by 1.8 percent and economies of scale rise by 1.7 percent in the investment goods sector. If imperfect competition is restricted to the basic materials/chemicals industry (IC_MMC), the overall demand elasticity of this sector reduces by more than 6.5 percent, and economies of scale drop by almost 7 percent. In the case of the investment goods industry being imperfectly competitive (IC_EQP), both its demand elasticity and scale economies rise by about 1.3 percent. The effect on demand elasticities and economies of scale in any imperfectly competitive sector is thus less pronounced if the other sector is perfectly competitive than it is if both sectors are imperfectly competitive.

Table 3.4 Change in demand elasticities (% change)

	PC	IC_MMC	IC_EQP	IC
MMC	-	-6.55	-	-7.05
EQP	-	-	1.35	1.82

Table 3.5 Change in economies of scale (% change)

	PC	IC_MMC	IC_EQP	IC
MMC	-	-6.83	-	-7.27
EQP	-	-	1.26	1.72

The induced changes in economies of scale imply that structural change is more pronounced under imperfect competition than under perfect competition. As shown in Table 3.2, the drop of basic materials/chemicals output is 50 percent larger if the basic materials/chemicals and investment goods industries are imperfectly competitive than it is in the perfect competitive case. Conversely, the increase of investment goods output is substantially enhanced if these two industries are characterized by imperfect competition.

3.3.3 Macroeconomic Effects

The macroeconomic effects are less dependent on the market structure than are the sectoral ones. Table 3.6 shows the required rate of the carbon tax and the induced percentage changes in macroeconomic indicators as compared to the benchmark level.

In the case of all markets being perfectly competitive the tax rate is around 36 ECU per ton of CO_2. The reduced utilization of fossil fuels leads to a reduction of welfare (measured as Hicksian equivalent variation HEV in income) by less than 0.1 percent and of GDP by one fourth percent. Wages and rental rates are almost 1.7 percent below BaU, indicating that reduced energy input implies a considerable drop in factor productivity at the given employment level.

The total costs of carbon abatement under imperfect competition can be higher or lower than those under perfect competition depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail. As discussed above, carbon taxes reduce economies of scale in the MMC sector and hence exacerbate the ‘competitive’ costs of carbon abatement. The reverse is true for imperfect competition in the EQP sector. If both sectors are imperfectly competitive, the induced efficiency losses in basic materials/chemicals dominate the efficiency gains in investment goods, and the welfare loss is larger than it is in the perfect competitive case.

On the whole the macroeconomic effects of carbon taxes for the German economy are slightly more unfavorable under imperfect competition compared to the competitive case because the negative effect in the MMC sector dominates the positive effect in the EQP sector.

Table 3.6 Carbon tax and macroeconomic effects (% change)

	PC	IC_MMC	IC_EQP	IC
Welfare (HEV)	-0.06	-0.13	-0.03	-0.09
GDP	-0.24	-0.30	-0.20	-0.26
Consumption	-0.41	-0.47	-0.39	-0.44
Investment	0.98	0.88	1.03	0.95
Wage rate	-1.69	-1.80	-1.60	-1.69
Rental rate	-1.66	-1.60	-1.72	-1.67
Exchange rate	-0.90	-0.83	-0.92	-0.85
Carbon tax*	35.64	35.20	35.66	35.20

* in ECU_{95} per ton of CO_2

3.4 Conclusions

In this chapter we analyzed the economic effects of environmental taxes in an open economy with imperfect competition. Under imperfect competition with free entry and exit, environmental taxes have an impact on economies of scale by changing the number and size of firms. Whether economies of scale rise or fall in a particular industry depends on induced changes in the price elasticity of demand. Because export demand is more price elastic than domestic demand, the overall price elasticity rises (falls) as the industry gains (loses) in comparative advantage.

Using a computable general equilibrium model for Germany we found that a unilaterally introduced carbon tax leads to a shift in comparative advantage in favor of the investment goods industry (EQP) and to the disadvantage of the basic material/chemicals industry (MMC). Under imperfect competition, these changes have direct consequences on the economies of scale, which are absent under perfect competition. Because of these effects, the structural change induced by carbon taxes was found to be more pronounced under imperfect competition as compared to perfect competition.

At the macroeconomic level, the total costs of carbon abatement under imperfect competition can be either higher or lower than those under perfect competition, depending on whether aggregate gains or losses in economies of scale across imperfectly competitive sectors prevail. In our simulations for Germany, the loss in economies of scale within MMC dominates the gains within EQP; on the whole the total costs of carbon abatement turn out slightly higher than under perfect competition.

The impact of imperfect competition on the structural change induced by environmental taxes has so far been little explored. Given that imperfect competition prevails in various goods markets, our findings suggest that the structural impacts of environmental taxes may be larger than previously assumed.

Appendix 3.A Algebraic Model Summary

This appendix provides an algebraic summary of the equilibrium conditions for the comparative-static model with perfectly competitive markets (see Section 2.3 for a detailed description and Appendix B for the extension with respect to the specification of imperfectly competitive good markets). Table 3.7 explains the notations for variables and parameters. Key elasticities are summarized in Table 3.8. Estimated Armington elasticities are given in Table 3.9. Table 3.10 gives sectoral benchmark capital and energy intensities. Sectoral markup rates are summarized in Table 3.11. For the sake of transparency, we do not write down the explicit functional forms but instead use the acronyms CES (constant elasticity of substitution), CD (Cobb-Douglas) and LT (Leontief) to indicate the class of functional form in place.

Zero Profit Conditions

Aggregate output:

$$\Pi_i^Y = P_i - LT\left[PA_{n,n\in N}, CES\left(PE_i, CES\left(PL, PK\right)\right)\right] \leq 0,\ \forall i \in V$$

$$\Pi_i^Y = P_i - CES\left[PR_i, LT\left(PL, PK, PA_j\right)\right] \leq 0,\ \forall i \in F \qquad \perp Y_i \qquad (3.A1)$$

Energy aggregation:

$$\Pi_i^E = PE_i \text{ - } CES\left[PA_{ELE}, CES\left(CES\left(PA_{HCO}, PA_{SCO}\right), CES\left(PA_{GAS}, PA_{OIL}\right)\right)\right] \leq 0,\ \forall i \in I \setminus ELE$$

$$\Pi_i^E = PE_i \text{ - } CES\left[PA_{ELE}, CES\left(PA_{OIL}, CES\left(PA_{GAS}, CES\left(PA_{HCO}, PA_{SCO}\right)\right)\right)\right] \leq 0,\ i = ELE$$

$$\perp E_i \qquad (3.A2)$$

Armington aggregation:

$$\Pi_i^A = PA_i \text{ - } CES\left(P_i, PM_i\right) - P^{CO2} a_i^{CO2} \leq 0 \qquad \perp A_i \qquad (3.A3)$$

World import good production:

$$\Pi_i^M = PM_i \text{ - } CES\left(PA_i, PFX\right) \leq 0 \qquad \perp M_i \qquad (3.A4)$$

Utility production:

$$\Pi^U = PU \text{ - } CD\left(PC, PINV\right) \leq 0 \qquad \perp U \qquad (3.A5)$$

Investment:

$$\Pi^{INV} = PINV \text{ - } LT\left(PA_{i,i\in I}\right) \leq 0 \qquad \perp INV \qquad (3.A6)$$

Final demand:

$$\Pi^{C} = PC - CES\left[CES\left(PA_{n,n\in N} \right), CES\left(PA_{ELE}, CES\left(PA_{HCO}, PA_{SCO}, CES\left(PA_{OIL}, PA_{GAS} \right)\right)\right)\right)\right] \leq 0 \qquad \perp C \qquad (3.A7)$$

Market Clearance Conditions

Labor:

$$\bar{L} \geq \sum_{i} Y_i \frac{\partial \Pi_i^Y}{\partial PL} \qquad \perp PL \qquad (3.A8)$$

Capital:

$$\bar{K} \geq \sum_{i} Y_i \frac{\partial \Pi_i^Y}{\partial PK} \qquad \perp PK \qquad (3.A9)$$

Natural resources:

$$\bar{Q}_f \geq Y_f \frac{\partial \Pi_f^Y}{\partial PR_f} \qquad \perp PR_f \qquad (3.A10)$$

Domestic output:

$$Y_i \geq A_i \frac{\partial \Pi_i^A}{\partial P_i} \qquad \perp P_i \qquad (3.A11)$$

Energy aggregate:

$$E_i \geq Y_i \frac{\partial \Pi_i^Y}{\partial PE_i} \qquad \perp PE_i \qquad (3.A12)$$

World import good:

$$M_i \geq A_i \frac{\partial \Pi_i^A}{\partial PM_i} + M_i^{ROW} \qquad \perp PM_i \qquad (3.A13)$$

Armington aggregate:

$$A_i \geq \sum_{j} Y_j \frac{\partial \Pi_j^Y}{\partial PA_i} + C \frac{\partial \Pi^C}{\partial PA_i} + INV \frac{\partial \Pi^{INV}}{\partial PA_i} + M_i \frac{\partial \Pi_i^M}{\partial PA_i} \qquad \perp PA_i \qquad (3.A14)$$

Private demand:

$$C \geq U \frac{\partial \Pi^U}{\partial PC} \qquad \perp PC \qquad (3.A15)$$

Investment:

$$INV \geq U \frac{\partial \Pi^{U}}{\partial PINV} \qquad \perp PINV \quad (3.A16)$$

Utility:

$$\mathrm{U} \geq \frac{INC}{PU} \qquad \perp PU \quad (3.A17)$$

Carbon emissions:

$$\overline{CO2} \geq \sum_{i} A_i \cdot a_i^{CO2} \qquad \perp P^{CO2} \quad (3.A18)$$

ROW closure:

$$\sum_{i} PM_i \cdot \underbrace{\theta_i \cdot \frac{INC^{ROW}}{PFX}}_{M_i^{ROW}} = \underbrace{\sum_{i} PFX \cdot \left(\frac{PM_i}{PFX}\right)^{\sigma_M} + \overline{B}}_{INC^{ROW}} \qquad (3.A19)$$

Foreign closure:

$$\sum_{i} \frac{\partial \Pi_i^{M}}{\partial PFX} \cdot M_i = \sum_{i} \left(\frac{PM_i}{PFX}\right)^{\sigma_M} \qquad \perp PFX \quad (3.A20)$$

Table 3.7 Sets, activity and price variables, endowments

Sets:	
I, i, j	Sectors and goods (13 commodities)
E, e	Energy goods (HCO, SCO, OIL, GAS and ELE)
N, n	Non energy goods
F, f	Fossil fuels (HCO, SCO, GAS)
V, v	Non fossil fuels
Activity variables:	
Y_{i}	Aggregate production
E_{i}	Aggregate energy input
A_{i}	Armington aggregate
M_{i}	World import aggregate
M_i^{ROW}	ROW import demand
U	Household utility
INV	Aggregate investment
C	Private consumption

Table 3.7 continued

Price variables:	
P_{i}	Output price
PE_{i}	Price of aggregate energy
PA_{i}	Price of Armington aggregate
PM_{i}	Price of world import aggregate
PFX	ROW export and import price
PU	Utility price index
PC	Price of aggregate household consumption
$PINV$	Price of investment demand
PL	Wage rate
PK	Price of capital services
PQ_{f}	Rent from natural resource
P^{CO2}	Price of carbon permit
Endowments:	
$\overline{L}$	Aggregate labor endowment
$\overline{K}$	Aggregate capital endowment
$\overline{Q}_f$	Endowment of natural resource f
$\overline{B}$	Balance of payment surplus
$\overline{CO2}$	Endowment with carbon emission rights
Other parameters:	
a_i^{CO2}	Per unit carbon coefficient
θ_i	Expenditure share of world import good i
σ_M	ROW export supply elasticity
INC	Income of representative agent
INC^{ROW}	ROW income

Appendix 3.B Specification of Imperfect Competition

As described in Section 3.2.2, each imperfectly competitive sector is modeled as a homogenous Cournot-Oligopoly, in which the output price is given as a markup on marginal cost (see Equation 3.1). The price elasticity included in the markup expression consists of several components, as described in Equation (3.4). These components are functions of substitution elasticities and value shares within the various aggregates.

If several goods $Z_1, ..., Z_N$ form a CES aggregate Z, the price elasticity of good $n \in (1,...,N)$ is:

$$\eta_n = \sigma \cdot (1 - \theta_n) \tag{3.B1}$$

where σ is the elasticity of substitution between the different goods and θ_n is the value share of good n, given that the level of the aggregate Z is seen as exogenous. If Z, in contrast, is a sub-aggregate in an aggregation hierarchy, one has to consider the price elasticity of Z, which depends in the same manner on the substitution elasticities and value shares of higher stages. This logic continues until a stage is reached that is no longer considered price dependent by the suppliers.

This reasoning implies that the component elasticities η_F and η_x in Equation (3.4) take the following form:

$$\eta_F = \sigma_A \cdot (1 - s_{YA}) \tag{3.B2}$$

$$\eta_X = \sigma_M \cdot s_{YA} \cdot (1 - s_{XM}) \tag{3.B3}$$

where σ_A = elasticity of substitution between domestic output and import in Armington aggregate A; σ_M = elasticity of substitution between German exports and ROW exports in world import composite M; s_{YA} = value share of domestic output in Armington aggregate; s_{XM} = value share of German Armington good exports in the world import composite.

Appendix 3.C Summary of Key Elasticities and Markup Rates

Table 3.8 Selected substitution elasticities

Production	
Capital-labor-energy vs. intermediates	0
Capital-labor vs. energy	0.6
Capital vs. labor	0.8
Electricity vs. primary energy inputs	0.3
Hard coal and lignite vs. gas and oil	0.5
Hard coal vs. lignite	2
Gas vs. oil	2
Hard coal, lignite and gas vs. oil in electricity production	0.5
Hard coal and lignite vs. gas in electricity production	2
Hard coal vs. lignite in electricity production	3
Consumption	
Energy goods vs. non-energy goods	0.5
Electricity vs. primary energy inputs	0.5
Hard coal and lignite vs. oil and gas	0.2
Oil vs. gas	0.3
Non-energy goods vs. non-energy goods	1
Trade	
Armington goods and ROW exports in world import good (σ_M)	16

*Table 3.9 Estimated Armington elasticities (σ_A) for Germany (1979-1991)**

Sector		Armington Elasticity	t-Value
MMC	Basic materials / chemical products	2.039	6.908
EQP	Investment goods	2.325	3.669

* See Böhringer et al. (2000b) for details. Armington elasticities for all other sectors are set equal to 2.

Table 3.10 Sectoral benchmark labor and energy intensities

	Labor intensity	Energy intensity	Energy/labor ratio
HCO	0.38	0.26	0.67
SCO	0.06	0.44	7.54
OIL	0.07	0.59	8.03
GAS	0.13	0.13	0.97
ELE	0.16	0.26	1.69
AGR	0.14	0.07	0.49
MMC	0.20	0.08	0.42
EQP	0.28	0.02	0.06
TRN	0.48	0.07	0.15
CSG	0.21	0.03	0.13
CST	0.36	0.02	0.07
SER	0.21	0.01	0.05
PUB	0.57	0.01	0.02

*Table 3.11 Sectoral markup rates**

	Markup rate
MMC	5.2
EQP	7.1

* based on Capros et al. (1997)

4 Market Power in International Emissions Trading [*]

4.1 Introduction

The Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC) imposes greenhouse gas emission limits for Annex 1 countries (i.e., the OECD countries and countries with economies in transition) as listed in Annex B of the Protocol. Together, Annex 1 countries must reduce their emissions of six greenhouse gases (GHG) by 5.2% below 1990 levels over the commitment period 2008-2012. The Protocol also incorporates emissions trading, joint implementation and the clean development mechanism (CDM) to help Annex 1 countries meet their Kyoto targets at a lower overall cost, but it leaves all of the details concerning these flexibility mechanisms open for further negotiations. The Protocol will become effective once it has been ratified by at least 55 parties whose CO_2 emissions represent at least 55% of the total emissions from all Annex 1 parties in the year 1990.

The sixth Conference of the Parties to the UNFCCC (COP6) held in the Hague, November 2000, aimed to finalize the procedures and institutions needed to make the Kyoto Protocol fully operational. During the negotiations leading up to the conference, the long and contentious policy debates centered on two issues. The first issue is to what extent Annex 1 countries could count their carbon absorbing forests and agricultural lands (the so-called sinks) against their emissions targets. The US were keen on the broadest and most generous definitions of sinks absorbing greenhouse gases in the atmosphere, while the Europeans

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[*] This chapter is based on the papers 'The Economic and Environmental Implications of the US Repudiation of the Kyoto Protocol and the Subsequent Deals in Bonn and Marrakech', with Z.X. Zhang, in: *Review of World Economics - Weltwirtschaftliches Archiv*, 138, 711-746, 2002, and 'Market Power in International Emission Trading - The Impacts of U.S. Withdrawal from the Kyoto Protocol', with C. Böhringer, in *Applied Economics*, 35 (6), 651-664, 2003.

wanted sharp curbs on the use of sinks. The clash between the US and the European Union (EU) over the extent of usage of the sinks to meet their emissions targets was blamed, in part, for the breakdown of the climate negotiations of the COP6. The second contentious issue is to what extent Annex 1 countries are allowed to use the flexibility mechanisms to meet their emissions targets. On the one hand, the US and other countries have advocated unrestricted emissions trading. On the other hand, the EU put forward a proposal for quantitative ceilings on the use of flexibility mechanisms (European Commission, 1999b), insisting that domestic abatement actions should be a main means of meeting emissions reductions required of each Annex 1 country (in other words, at least half of the emissions reductions required have to be undertaken domestically). This supplementary requirement caused the deepest division between the EU and the Umbrella Group countries (i.e. Japan, US, Switzerland, Canada, Australia, Norway, New Zealand) and was regarded as one of the main causes for the collapse of the COP6.

Soon after coming into office, the President Bush decided that the US would withdraw from the Kyoto Protocol. Quick to accept that the US would not re-enter the negotiations, the EU led a sustained diplomatic effort to keep the Kyoto Protocol alive (Legge, 2001). While the developing countries moderated some of their demands, the EU softened its stance on the extent of usage of sinks and flexibility mechanisms to secure the reluctant support of other Umbrella Group members for the Protocol at the resumed COP6 held in Bonn, July 2001. After tough negotiations, the political compromises were eventually reached on a number of key implementation issues of the Kyoto Protocol. This political deal, the so-called Bonn Agreement, was translated into the detailed legal text, the so-called Marrakech Accords, at the seventh Conference of the Parties (COP7) to the UNFCCC held in Marrakech, November 2001, which was expected to be easy but turned out to be another difficult meeting. The Kyoto Protocol, as detailed in the Marrakech Accords, has been rendered fit for its ratification in 2003.

The Bonn Agreement allows for significant credits for carbon dioxide sinks. With the US withdrawal from the Kyoto Protocol, the EU dropped its previous insistence on a cap on the use of flexibility mechanisms. The final wording at the Bonn Agreement is now that ‘domestic action shall thus constitute a significant element of the effort’ by each Annex 1 country. This is a very important and positive development because it will allow countries and businesses to reduce their emissions wherever it is cheapest to do so. Ironically, it is a development that the US had lobbied intensively for during previous rounds of international climate negotiations.

Earlier economic modeling studies focus on investigating economic efficiency and environmental effectiveness of meeting the original Kyoto reduction target of 5.2%, with and without considering the imposition of restrictions on the use of emissions trading (e.g. Ellerman and Decaux, 1998; Ellerman, Jacoby and Decaux, 1998; Bernstein et al., 1999; Bollen et al., 1999; Criqui et al., 1999; Manne and Richels, 1999; Criqui and Viguier, 2000; Ellerman and Wing, 2000; Paltsev, 2000b; Zhang, 2000b, 2001). The results, among others, show that the US is expected to be the biggest single buyer on the international market of tradable permits, and that restrictions on the use of emissions trading to comply with the Kyoto emissions targets will result in substantial efficiency losses. The most recent studies focus on the implications of the US withdrawal from the Protocol. A large part of these studies assume perfectly competitive behavior, and show that the US non-ratification leads to a sharp drop in the price of permits on the international market so that the remaining Kyoto-constrained Annex 1 countries can meet their Kyoto targets at much lower costs (Den Elzen and de Moor, 2001; Eyckmans et al., 2001; Hagem and Holtsman, 2001).

Given the small number of sellers in the Annex 1 market, namely the Eastern European countries and, particularly, the former Soviet Union, monopolistic supply behavior seems a realistic assumption. Dominant sellers might defer portion of their excess emissions permits for use in subsequent periods or exploit their market power on the permits market (Buchner et al., 2001; Manne and Richels, 2001). Manne and Richels (2001) have examined the implications of allowing banking of permits, an intertemporal flexibility that allows countries to carry permits that are unused in one commitment period forward for use in the subsequent periods. Several studies have explored the implications of organizing a sellers' cartel. But, in our view, there is an ample space for non-competitive supply behavior under Annex 1 emissions trading, and the realistic scenario of market power may lie somewhere in between the extreme scenarios of the perfect competition and the coordinated monopoly. Taking account of sinks credits as agreed in Bonn and Marrakech, this chapter aims to illustrate how market power could be exerted in the absence of the US ratification under Annex 1 trading and to explore the potential implications of the non-competitive supply behavior for the international market of tradable permits, compliance costs for the remaining Annex 1 countries, and the environmental effectiveness. Section 4.2 provides baseline emissions in

2010 for all Annex 1 regions, effective emissions reductions in all Kyoto-constrained Annex 1 regions and the size of hot air for those Kyoto-unconstrained Annex 1 regions. Section 4.3 discusses the analytical framework to study the effects of non-competitive supply behavior in the absence of the US ratification under Annex 1 emissions trading. Section 4.4 describes our partial equilibrium model based on marginal abatement cost curves, with the mathematical exposition of the model given in Appendix 4.B. Section 4.5 presents the policy scenarios examined, whereas Section 4.6 discusses all simulation results. Section 4.7 provides a sensitivity analysis of our findings. The chapter ends with the main conclusions and lines for further research.

4.2 Baseline Emissions, the Mandated Reductions and Size of Hot Air

The magnitude and distribution of abatement costs of meeting the Kyoto emission constraints depend crucially on the business-as-usual (BaU) projections for emissions. This study takes the year 2010 as representative of the first commitment period 2008-2012. Like other economic modeling studies on compliance costs (see Weyant, 1999), the study focuses only on CO_2, partly because CO_2 is the most important of the six greenhouse gases considered under the Kyoto Protocol, and partly because of lack of appropriate abatement cost data for non-CO_2 greenhouse gases.[28] Moreover, because it is a daunting task to estimate the marginal abatement cost for each Annex 1 country, we do so at a regional level. We aggregate Annex 1 countries into seven regions: Australia and New Zealand (AUN), Canada (CAN), Europe Union (EUR), Japan (JPN), the US (USA), Eastern Europe (EEC) and the former Soviet Union (FSU) (see Table 4.5 for the corresponding Annex 1 countries covered in each region). The first five Kyoto-constrained regions belong to the Organisation for Economic Co-operation and Development (OECD). Historical CO_2 emissions for each Annex 1 country in the base year 1990 as well as its projected CO_2 emissions in 2010 are derived from the US Department of Energy (DOE, 2001). They are aggregated into the above seven Annex 1 regions, as given in Table 4.1. The table also contains the nominal percentage reductions with

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[28] Inclusion of non-CO_2 greenhouse gases will lower absolute compliance costs, given that other greenhouse gases but CO_2 can be cut at lower costs. But, as Manne and Richels (2001) point out, the focus on CO_2 would not alter the general insights from this kind of analysis.

respect to (wrt) 1990 emissions levels and the effective percentage reductions with respect to baseline emissions in 2010 for both the original Kyoto emissions targets and the revised targets under the Bonn Agreement and the Marrakech Accords. The latter are based on the preliminary estimates by the European Commission factoring into the amount of sinks credits as agreed in Bonn and Marrakech (Nemry, 2001). As a result of allowing countries to count the amount of sinks credits, the average reduction target for the Annex 1 countries as a whole is reduced to 1.9%, in comparison to the original reduction target of 5.2% (see Table 4.1).

It can be seen that CO_2 emissions in all the OECD countries in 2010 are expected to continue to rise under the BaU scenario. Consequently, their effective percentage reductions from their projected baseline emissions are much higher than their nominal percentage reductions. Even if the sinks credits are factored into, meeting the Kyoto targets still requires a drastic reduction in emissions for AUN, CAN, EUR, JPN and USA.

The situation in the former Soviet Union and Eastern Europe is quite different. The economic transition led to a large decline in emissions as economies contracted and energy markets were deregulated since the collapse of the Soviet Union. By 1996, greenhouse gas emissions in these countries had declined 20-46% below their base year levels (Zhang, 2001). Although economies are projected to begin recovering during the period under review, emissions in most countries with economies in transition in 2010 are expected to remain below their base year levels. In other words, these countries are allocated assigned amounts under the Kyoto Protocol that exceed their anticipated emissions requirements even in the absence of any limitation. If emissions trading were allowed, these countries would be able to trade these excess emissions to other countries, thus creating the hot air that would otherwise have not occurred in the absence of emissions trading. Because the transfer of the hot air does not represent any real emissions reductions by the selling countries, allowing the acquisition of the surplus from the selling countries to meet the buying countries’ commitments makes the total emissions higher than what would be in the absence of emissions trading, although not above the aggregate Kyoto targets.

The hot air problem is particularly acute in Russia and the Ukraine. But the exact amount of hot air is by its nature uncertain. It depends particularly on expectations for economic recovery and developments in the energy sector in Russia and Ukraine. Optimistic expectations for economic recovery increases benchmark carbon emissions in 2010, shifting aggregate demand curves outwards and aggregate supply curves inwards on the international permit market, leading to a smaller amount of hot air than those projected based on less optimistic expectations for economic recovery. Most economic modeling studies project a size of hot air in the range from 111 MtC to 374 MtC in 2010 (Paltsev, 2000; Zhang, 2000b). Our projections of hot air for Russia and the Ukraine are based on the most recent projections for baseline carbon emission by the US Department of Energy (DOE, 2001). As indicated in Table 4.1, comparing the official DOE baseline projections for 2010 with the revised Kyoto emissions targets suggests a size of hot air of 296 MtC for FSU and 56 MtC for EEC. The withdrawal of the US as the world largest potential buyer of emissions permits leads to an excess supply of hot air of 54 MtC. If emissions permits were fully tradable among all remaining Annex 1 countries, a competitive market of permits would drive down the international price of permits to zero so that no real emissions reductions in Annex 1 countries at all would occur with respect to their BaU emissions.

Table 4.1 Quantitative implications of the Marrakech Accords

Region[a]	Baseline emissions (MtC)[b]		Nominal reduction (% wrt 1990)[c]		Effective reduction (% wrt 2010)		Absolute cutback (MtC wrt 2010)	
	1990	2010	w/o sinks	w/t sinks	w/o sinks	w/t sinks	w/o sinks	w/t sinks
AUN	88	130	– 6.8	– 9.4	27.6	25.9	36	34
CAN	126	165	6.0	– 5.2	28.2	19.7	47	32
EUR	930	1040	7.8	6.2	17.5	16.1	182	168
JPN	269	330	6.0	1.1	23.4	19.4	77	64
EEC	279	209	7.1	4.9	– 24.0	– 26.9	-50	– 56
FSU	853	593	0	– 4.2	– 43.8	– 49.8	–260	– 296
Total w/o US[d]	2545	2467	4.3	0.9	1.3	– 2.2	32	– 54
USA	1345	1809	7.0	3.7	30.9	28.4	558	514
Total w/t US[e]	3890	4276	5.2	1.9	13.8	10.8	590	460

[a] AUN – Australia and New Zealand; CAN – Canada; EUR - OECD Europe (including EFTA); JPN – Japan; EEC - Central and Eastern European countries; FSU - Former Soviet Union.

[b] Baseline emissions in 2010 based on DOE (2001) reference case.

[c] Estimates based on UNFCCC and FAO data (Nemry, 2001).

[d] Annex 1 total without the US ratification.

[e] Annex 1 total with the US ratification.

4.3 The Effects of Market Power in International Emissions Trading

A number of theoretical and empirical studies have examined the issue of market power on tradable quota markets (e.g., Hahn, 1984; Misiolek and Elder, 1989; Malueg, 1990; Westkog, 1996; Sartzetakis, 1997; Burniaux, 1998; Ellerman and Decaux, 1998; Ellerman and Wing, 2000; Godby, 2000). They show that either dominant buyers (monopsony/oligopsony) or sellers (monopoly/oligopoly) may be able to exert market power on the permit market or use its market power on the permit market to gain power in the product market. In the following discussion, market power refers only to the capacity to influence the market price of traded permits (‘cost minimizing manipulation’).

The impact of market power on the price of permits depends on who resides in such a power. In the case of a monopsony, market power under emissions trading results in reduced demand, whereas in the case of a monopoly market power under emissions trading results in reduced supply. A monopsonist may thereby force the permit price below, a monopolist above the competitive level (Misiolek and Elder, 1989). Thus, the extent of competition on a tradable permit market affects the efficiency of international emissions trading and the degree to which potential cost savings are realized. Permit price manipulations result in additional economic costs to achieve the same level of abatement as under a perfect competition and increase the costs of compliance. Whether market power is a real issue in an international greenhouse gas emissions trading depends on how such a trading scheme will take place. In general, the likelihood of market power increases if the number of participants is smaller or if the size of some participants is larger than neo-classical firm-to-firm trading with many participants (Woerdman, 2000). Article 17 of the Kyoto Protocol creates an intergovernmental emissions trading market next to inter-source trading.[29] In case of inter-source trading in which sub-national entities (e.g., firms) are authorized to trade on the international emissions permit market, the scope of market power seems rather limited.[30] Emissions trading modeled

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[29] See Zhang (1998, 2000a) for a detailed discussion on inter-governmental emissions trading and inter-source trading.

[30] Incorporating sub-national entities into an international emissions trading scheme would potentially increase the total amount of transactions in the international scheme. Increasing the number of trades would help to improve market liquidity and reduce the potential for abuse of market power. Hargrave (1998) shows that if an upstream trading system, which targets fossil fuel producers and importers as regulated entities, were implemented in the US, the total number of allowance holders would be restricted to about 1900. Even with such a relatively small number of regulated sources, market power would not be an issue. In the above upstream system for the US, the largest firm has only a 5.6 percent market allowance share. Firms, each having less than one percent share, would hold the lion’s share of allowances (Cramton and Kerr, 1998).

in many economic studies (Weyant, 1999) operates as if governments retain the sole right to trade. As such, emissions trading takes place on a government-to-government basis. Since the majority of inexpensive emissions permits are concentrated in a small number of countries, namely the Eastern European and former Soviet Union countries, these countries may be able to exert market power in order to drive up the international carbon price and extract sizeable economic rents under this trading scheme. On the demand side, competitive behavior seems to be the appropriate assumption. The reason is that either firms of the OECD countries are allowed to engage in emissions trading directly as proposed in the recent EU-wide emissions trading scheme,[31] or coordination of several individual OECD countries to organize a buyers' cartel seems rather difficult in case of intergovernmental emissions trading.

Given the revised emissions targets at the COP7, the effects of supply side restrictions are illustrated in Figure 4.1. The amount of hot air (H) is greater than the total abatement requirements of non-US Annex 1 countries (Q_u). Consequently, market price under perfect competition is zero ($P_u = 0$) and the quantity of permits traded equals the total abatement requirement (Q_u). There is no domestic abatement of Kyoto-constrained Annex 1 countries. Emissions of permit importers equal the BaU emission levels $\left(\bar{e}\right)$. Total revenues for permit exporting countries equal zero. With supply side restrictions, the supply of permits is reduced from S_u to S_r. This drives up the market price of permits from P_u to P_r. The total volume of permits traded is reduced from Q_u to Q_r. The exercise of monopoly power entails a redistribution of the gains from emissions trading from buyers to sellers and a loss of efficiency. Permit exporters receive the rectangle *IJK0*, which represents the total income from permit sales. They benefit from further supply restrictions as long as the gains from higher prices are greater than the loss of revenues from a lower level of permits sold. Due to the higher price of permits, importing countries increase domestic abatement (a), thus reducing emissions from BaU emissions $\bar{e}$ to e. The remaining abatement requirements up to the revised Kyoto target (k) is met through permit import (q). The costs of compliance for a permit importer increase to *LMNW*, of which *LMVW* is the income transfer to permit exporters and *MNV* is the increased resource cost (deadweight loss). The economic efficiency

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[31] On 23 October 2001, the Commission of European Communities (European Commission, 2001) adopted a proposal for implementing EU-wide emissions trading. Such a scheme involves company trading, should start in 2005, and in the first phase only covers CO_2 emissions from large industrial and energy activities. These activities of about 4000-5000 major polluters are estimated to account for about 46% of the EU's total CO_2 emissions in 2010.

of emissions trading is reduced under market power since marginal abatement costs (*C'*) are not equalized across regions. The loss in efficiency relative to the competitive case depends on the amount of permits initially allocated to the regions (Hahn, 1984). With non-competitive supply behavior, some part of hot air is suppressed (Q_u – Q_r) and thus the environmental effectiveness is increased.

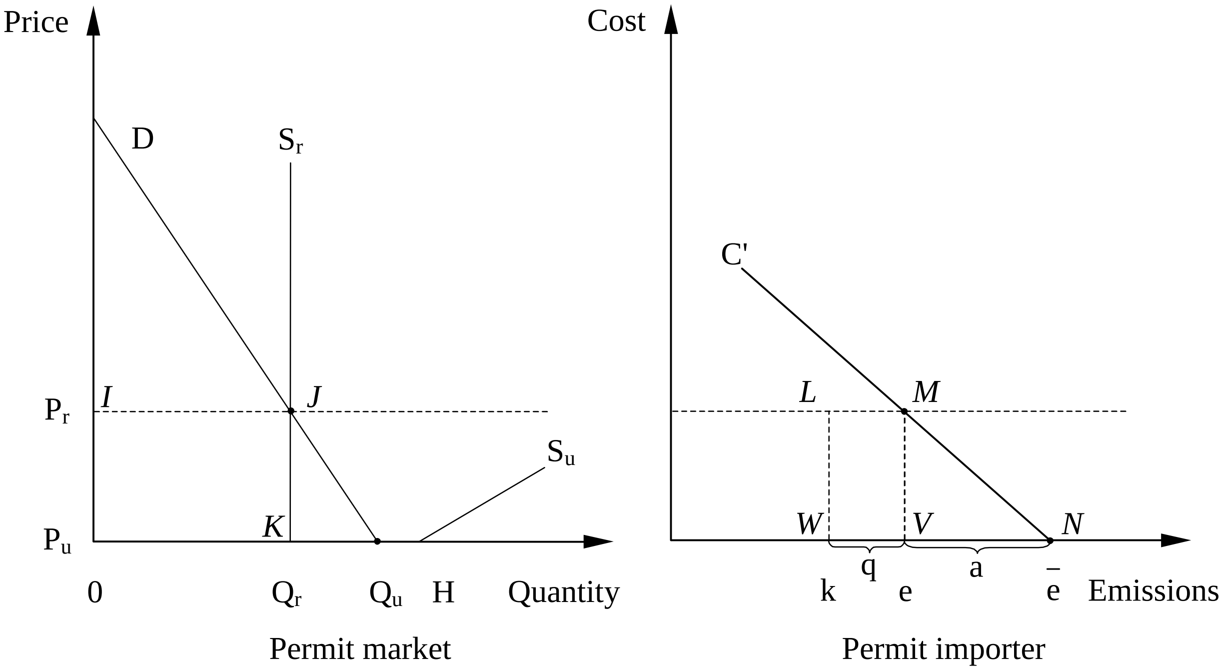

Figure 4.1 Effects of supply side restrictions

4.4 Partial Equilibrium Model of Non-competitive Supply Behavior

We assess the effects of non-competitive supply behavior in a partial equilibrium set-up using marginal abatement cost (MAC) curves for different Annex 1 regions in the year 2010 (see Appendix 4.B for the mathematical exposition of the model). These curves represent the marginal cost of reducing carbon emissions by different amounts within an economy. Marginal costs of abatement differ considerably across countries due to differences in the carbon intensity, initial energy price levels and the substitution possibilities in the respective economy.

The MAC curves used here are generated by the world energy system model POLES (Criqui et al., 1996), which embodies a detailed bottom-up description of regional energy markets and world-wide energy trade. To get the marginal abatement cost curves, we run the model under progressively more stringent carbon constraints for the year 2010. The shadow price of carbon is plotted against the abatement levels and we fit a constant elasticity function to the model results using a least-squares procedure. The coefficients of the marginal abatement cost curve approximations of the form $\text{MAC} = \alpha \cdot (\text{ABATEMENT})^{\beta}$ are given in Table 4.2, where MAC is measured at 1995 US$ per ton of carbon (accordingly, all cost or price-related numbers derived afterwards are measured at 1995 US$) and the amount of carbon abatement (ABATEMENT) is in million tons of carbon.[32] The MAC analysis is a partial equilibrium approach since it does not consider all the spillover effects of carbon abatement policies and monopolistic pricing on other markets. For instance, abating countries do not take into account the effects of carbon reduction efforts on energy prices and thereby its terms of trade.[33] However, it provides a convenient way to analyze the effects of different assumptions on non-competitive supply side behavior.

Table 4.2 Coefficients of MAC curve approximations $\text{MAC} = \alpha \cdot (\text{ABATEMENT})^{\beta}$

Coefficients	AUN	CAN	EEC	EUR	FSU	JPN	USA
α	0.675	1.567	0.316	0.114	0.046	0.718	0.020
β	1.442	1.379	1.388	1.369	1.482	1.338	1.427

The marginal abatement cost curves for the Kyoto-constrained Annex 1 regions, namely Australia and New Zealand (AUN), Canada (CAN), OECD Europe (EUR), and Japan (JPN) as well as the US (USA), are displayed in Figure 4.2. From these MAC curves we can derive the aggregate demand curve for permits of the Kyoto-constrained, i.e. importing Annex 1 regions, with and without the US participation. An Annex 1 region demands permits as long as the market price of permits is lower than its autarkic marginal abatement costs. Conversely,

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[32] This implies that we assume that all abatement actions take place in 2010 as many other modelers do (Weyant, 1999). As a result, marginal abatement costs are estimates at a specific point in time (i.e., without considering the time path of abatement actions), namely, 2010 in our exercise. Nevertheless, Ellerman and Decaux (1998) show that MAC curves generated in this way are robust with regard to emissions trading policies (i.e. different levels of abatement among regions and the scope of emissions trading).

[33] The impacts of market power in permit markets in a general equilibrium set-up are analyzed in Böhringer and Löschel (2003c) using an extended version of the CGE model introduced in Chapter 2.

it supplies permits as long as the market price is above its autarkic marginal costs of abatement. The demand curve is then obtained by simply adding up the potentially demanded and supplied quantities of all Kyoto-constrained Annex 1 regions at each market price. If the market price is equal to zero, which is the result under the assumption of perfect competition, all constrained Annex 1 regions demand their Kyoto emission reduction requirements, which sum up to 298 MtC and 812 MtC without and with the US participation, respectively. As the price increases, the aggregate demand diminishes. When the market price reaches 108 US$/tC, the autarkic marginal abatement cost of AUN, this region switches from demanding to supplying permits. The same happens at a price of 127 US$/tC for EUR. At a price of 140 US$/tC, the amount of permits supplied by AUN (7 MtC) and EUR (12 MtC) just equals the demand by CAN (6 MtC) and JPN (13 MtC) resulting in an aggregate excess permit demand (without the US) of zero.

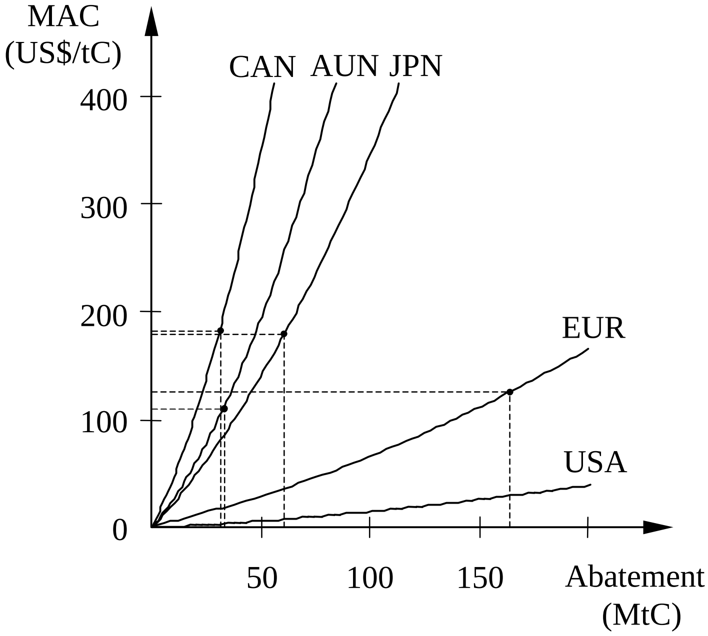

Figure 4.2 Marginal abatement cost curves for Kyoto-constrained Annex 1 regions

4.5 Formulation of Policy Scenarios

Using the marginal abatement cost curves of seven Annex 1 regions and the excess market demand curve for permits (the curve D without the US participation and D_{US} with the US participation in Figure 4.5), we will examine the following policy scenarios:

NOTRADE	Each Annex 1 country must individually meet its Kyoto targets without any trading of permits across national borders. This is equivalent to a case in which each Annex 1 country applies domestic carbon tax that is high enough to meet its individual Kyoto commitment. With the EU backing off earlier demand for placing quantitative limits on trading, this scenario seems unlikely. But it provides a useful reference point for examining the potential efficiency gains of emissions trading and the corresponding environmental effectiveness.
TRADE	All Annex 1 countries including FSU and EEC are allowed to trade emissions permits with each other. Under the assumption of perfectly competitive supply and demand behavior, all regions behave as price takers. There is no market power exercised on the international permit market. We consider two variants: one with the US (TRADE w/t US), and one without the US (TRADE w/o US). This distinction aims to examine how the US withdrawal from the Protocol affects compliance costs of other Annex 1 countries and environmental effectiveness vis-à-vis full Annex 1 trading.

As discussed in Section 4.3, the assumption of perfectly competitive supply behavior seems unrealistic. Given FSU and EEC as the dominant suppliers of emissions permits on the international market, it is not in their interest to sell excess permits at zero price. To illustrate how market power could be exerted under Annex 1 trading without US participation and to explore the effects of the non-competitive supply behavior, we set up the following three scenarios:

CARTEL	FSU and EEC coordinate their permit supply to maximize joint profits forming a sellers' cartel. This is in effect a monopoly, and the members of the cartel share the monopolistic profits. All other regions behave as price takers, i.e. they minimize their abatement costs given the permit price set by the two regions.
NASH	FSU and EEC behave non-cooperatively and do not coordinate their permit supply. Instead, they act independently of each other, with each region

	attempting to maximize its profits by choosing its own permit supply. This structure on the permits market is analyzed for a duopoly competing in quantities using the Nash equilibrium concept.
MONOP	Only FSU acts as a monopoly. EEC is treated as a competitive fringe (price taker) following the price leadership of the dominant supplier FSU.

4.6 Simulation Results

4.6.1 NOTRADE

Without emissions trading, each Annex 1 country must meet its Kyoto abatement commitment as indicated in Table 4.1 by solely undertaking domestic abatement actions. The autarkic marginal costs of abatement are 108 US$/tC for AUN, 127 US$/tC for EUR, 190 US$/tC for CAN and 187 US$/tC for JPN. The autarkic marginal abatement cost for USA in the case of its compliance with the Kyoto Protocol is 148 US$/tC. EEC and FSU do not face any binding abatement requirements and thus their autarkic marginal costs of abatement are zero. The total costs of abatement without trade, which represent the areas under the marginal abatement cost curves, are US$ 1.5 bn for AUN, US$ 2.6 bn for CAN, US$ 9.0 bn for EUR, US$ 5.1 bn for JPN and US$ 31.3 bn for USA. In terms of relative compliance cost measured as a percentage of the official DOE (2001) projection for GDP in 2010, EUR bears by far the smallest compliance burden (0.08% GDP loss). With 0.27% GDP loss, CAN is hit hardest. With the loss of US$ 31.3 bn and 0.24% GDP, the costs for USA are among the highest in both absolute and relative terms. The total compliance costs of Annex 1 countries including the US amount to US$ 49.5 bn (0.15% GDP loss). With respect to the environmental effectiveness, the absence of the US ratification leads to a real emission reduction of 298 MtC (7.0% effective reduction from the total Annex 1 baseline emissions in 2010), whereas an effective emission reduction with the US ratification amounts to 812 MtC, or 19.0% below the total Annex 1 baseline emissions in 2010.

In what follows, we will discuss the effects of emissions trading under the different policy scenarios considered subsequently. Unless otherwise specified, all the numbers cited in this section are given in Table 4.3.

4.6.2 TRADE – The Effects of Annex 1 Emissions Trading under Perfect Competition

4.6.2.1 TRADE w/o US

In the absence of the US ratification, the price of permits under perfect Annex 1 trading equals zero – assuming no transaction costs – since the amount of hot air exceeds the total amount of the revised emissions reductions required of all remaining Kyoto-constrained Annex 1 regions. None of the remaining Annex 1 countries with effective abatement requirements abate domestically at all, and their total compliance costs for meeting the revised Kyoto emissions targets are zero. Their total gains from emissions trading, namely the reductions in the total compliance costs relative to the no emissions trading case, amount to US$ 18.2 bn (0.09% of GDP). But the magnitude of the gain of each region depends on the relative differential between its autarkic marginal cost and the market price of permits. *Ceteris paribus,* regions whose autarkic marginal costs differ significantly from the trading equilibrium price (i.e. EUR, JPN) trade more and thus benefit more than those regions with autarkic marginal abatement costs closer to the permit price (of zero), i.e. AUN.[34] The same reasoning applies to permit exporters. The farther away the permit price is from the autarkic marginal abatement costs, the more revenues they are able to receive from selling excess permits. With perfect competition, the autarkic marginal abatement costs of permit exporters FSU and EEC equal the permit price. Consequently, these two regions do not benefit at all from emissions trading.

It should be pointed out that while all remaining Kyoto-constrained Annex 1 regions benefit from excess supply of hot air from FSU and EEC in the absence of the US ratification, the environmental effectiveness under unconstrained Annex 1 trading drops to zero in comparison with a reduction of 19.0% from the total Annex 1 baseline emissions in 2010 in the case where all Annex 1 countries including the US ratify the Kyoto Protocol and trading across Annex 1 countries is not allowed. In other words, under unrestricted emissions trading, Kyoto comes at no costs because the world economy and its emissions develop as in the

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[34] Under this scenario, all regions just trade their emission reduction requirements. Therefore, the trade volume is larger for AUN than for CAN.

business-as-usual case. The total Annex 1 carbon emissions in 2010 remain unchanged at about 2.5 gigatons of carbon (GtC).

4.6.2.2 TRADE w/t US

When all Annex 1 countries including the US are allowed to trade emissions permits, the marginal cost of domestic abatement for each Annex 1 region equalizes. The resulting market price of permits is equal to US$ 41 per ton of carbon. The total market size (i.e. total volume of traded permits) is estimated at 482 MtC. All Kyoto-constrained Annex 1 regions are permit importers. By contrast, all Kyoto-unconstrained Annex 1 regions are permit exporters. Unlike the case of US non-ratification, both regions sell not just hot air, but are also involved in domestic abatement actions: EEC abates 33.1 MtC and FSU 97.3 MtC domestically. The total Annex 1 compliance costs are reduced from US$ 49.5 bn in the case of no emissions trading (NOTRADE) to US$ 7.7 bn with trading. At the same time, trading across all Annex 1 countries leads to a real emission reduction of 460 MtC, or 10.8% below the total Annex 1 baseline emissions in 2010.

4.6.3 CARTEL – EEC and FSU Coordinate Permit Supply

Our first specification of non-competitive behavior looks at the cooperative solution. The strategies of EEC and FSU are coordinated so as to attain the best result for the group. In so doing, they form a cartel and act as a monopoly in order to maximize its profit from permit sales, which is then divided among themselves by some prearranged rule. The cartel faces the downward sloping residual excess demand curve (the curve D in Figure 4.5). The aggregate cartel restricts the supply of permits until the marginal revenue from permit sales is equal to marginal abatement cost, i.e. equal to zero for hot air supply. At this point, the higher price just compensates for the decrease in the quantity exported, and the demand elasticity is equal to unity. The more inelastic the excess demand curve facing the cartel, the higher the price the cartel can set and the greater its profit. Monopolization has the expected effects: the cartel supplies only 126 MtC permits to the market. The market price with monopolistic supply is raised to 66 US$/tC in comparison with zero in the absence of the US ratification under perfect Annex 1 trading. This is the maximum price that can be attained with supply side restrictions. Consequently, gains from trading are reduced from US$ 18.2 bn under perfect competition to US$ 13.4 bn under a supply cartel (see Table 4.3). This is mainly because Kyoto-constrained Annex 1 regions suffer from a substantial loss (US$ 13.1 bn) in comparison with the case of perfectly competitive trade.

The loss of Kyoto-constrained Annex 1 regions is split up into incurred cost of domestic abatement and transfers made to permit suppliers. The increased resource costs due to domestic abatement add up to US$ 4.8 bn: US$ 0.6 bn for AUN, US$ 0.4 bn for CAN, US$ 2.9 bn for EUR and US$ 0.8 bn for JPN. The total expenditures for permit purchases amount to US$ 8.3 bn: US$ 0.6 bn for AUN, US$ 1.1 bn for CAN, US$ 4.2 bn for EUR, and US$ 2.3 bn for JPN. Despite the efficiency losses, all Kyoto-constrained Annex 1 regions are still better off with emissions trading under a supply cartel than under no trading at all. In comparison with the case of no emissions trading, they gain US$ 5.2 bn.

Expenditures for permit purchases are transferred to the cartel suppliers EEC and FSU. Thus, the total (maximum) gain of the cartel equals the total expenditures for permit purchases, which amount to US$ 8.3 bn. In comparison with zero profits from permit sales under a perfect competition, such dramatic increases in profits enhance the incentive for the two regions to coordinate their permit sales. The cartel must decide how the monopoly profit of the cartel is to be divided among EEC and FSU. The range of possible cooperative solutions can be narrowed down. The payoffs to the two participants cannot add up to more than US$ 8.3 bn. Since each region can choose to go alone, neither will accept a payoff less than under the NASH scenario derived later (US$ 3.1 bn for EEC and US$ 4.4 bn for FSU). Thus, all points on the solid line AB in Figure 4.3 are possible solutions to the bargaining problem (solution set). There have been several cooperative game solution concepts proposed. We consider only the egalitarian solution here. The symmetric or even split point is given by E (US$ 0.4 bn for EEC, US$ 0.4 bn for FSU). The profit of EEC amounts then to US$ 3.5 bn, that of FSU to US$ 4.8 bn. It is undecided, however, how much is supplied to the market by each region. If, for example, EEC supplies its 56 MtC of hot air, it receives US$ 3.7 bn from permit sales and must pay US$ 0.2 bn as a side payment to FSU. Given the larger bargaining power by FSU, the cooperative solution may lie more towards point A.

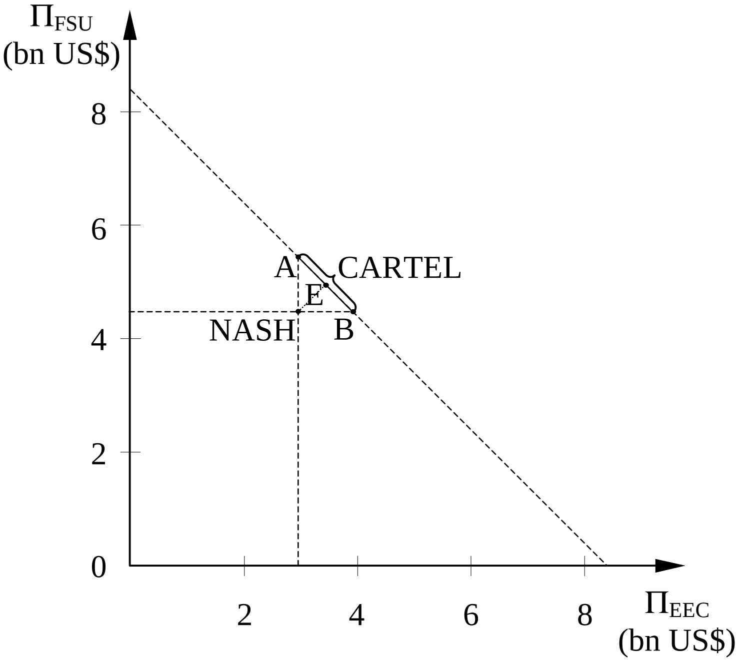

Figure 4.3 Imputation of monopolistic profits

Under a monopolistic cartel supply, all Kyoto-constrained Annex 1 regions' demand for permits drop from 298 MtC under a perfect competition to 126 MtC. This means that 172 MtC of hot air are suppressed. Annex 1 emissions are reduced from 2.5 GtC to about 2.3 GtC, i.e. the environmental effectiveness of the Kyoto protocol is increased by market power on the supply side. Generally speaking, the derived results are expected to be sensitive to the assumptions about the amount of hot air. While this may be particularly the case under the no trade scenario (NOTRADE), the amount of hot air is a far less critical factor under the monopolistic cartel supply examined here, since in this case FSU and EEC supply the complete market with only 126 MtC, i.e. about one third of the hot air assumed in the calculations.

The formation of a permit supply cartel does not seem implausible. The cartel has a good ability to raise permit prices since the excess demand curve is relatively vertical (inelastic). No workable punishment is foreseen to be put in place, since EEC and FSU can otherwise bank their excess hot air permits for subsequent commitment periods as allowed under Article 3.13 of the Kyoto Protocol. The organizational costs are low, in particular due to the regular meetings at the Conference of Parties (COP). But each member of the cartel has an incentive to supply more permits than is best for the cartel collectively. As a result, the cartel tends to break apart. Whether this is going to happen depends on the regions' willingness to commit themselves to efficiently coordinated strategies, which in turn boils down to the design of an international emissions trading scheme. This is the greatest challenge ahead for EEC and FSU to reap monopolistic profits from coordinating their permit sales, given that the two regions comprise of a number of countries.

4.6.4 NASH: EEC and FSU as a Cournot Duopoly

The second specification of non-competitive behavior assumes that EEC and FSU act independently of each other, with each region attempting to maximize its profit by choosing its own permit supply. We use a Cournot model of duopoly, where the two regions simultaneously set their quantity supplied to the permits market. Both regions have to consider their rival region's behavior to determine their own optimal choice of permit supply. The maximum profit action by one region, given its beliefs about the action taken by its rival, is represented by the best-response (or reaction) function. A Nash equilibrium corresponds with an intersection of the two best-response functions. In the Nash equilibrium, no player has an incentive to deviate from his prescribed strategy. Each region sells the quantity of permits that maximizes its profits given its (correct) beliefs about other regions' choice of permit supply. Reaction curves are drawn in Figure 4.4. The best response function of FSU (BR_{FSU}) has two significant points: if EEC supplies zero permits, FSU provides 126 MtC. This is the cartel (monopoly) output level, since a Cournot player without competition faces the market demand curve. If EEC supplies 298 MtC, the total emission reduction required of the Kyoto-constrained Annex 1 regions, FSU provides zero permits. However, the two regions are not identical. FSU has hot air of 296 MtC and will not be engaged in any abatement activities. EEC, on the other hand, has hot air of only 56 MtC. The permit exports beyond the amount of hot air are generated by undertaking domestic abatement efforts to earn additional profits. EEC abates domestically up to the point where the marginal abatement cost of generating one additional permit equals its marginal revenue. This is the reason why the best response function of EEC (BR_{EEC}) is kinked: the best response function is symmetric to the one of FSU if only hot air is supplied, but differs in the case of domestic abatement efforts by EEC. If FSU supplies zero permits, EEC provides only 87 MtC, i.e. hot air of 56 MtC and an additional 31 MtC resulting from domestic abatement action. Again, if FSU supplies 298 MtC, EEC offers zero permits. In the Nash equilibrium, FSU exports permits of 96 MtC and

EEC permits of 70 MtC. The total market supply of permits amounts to 166 MtC, and the corresponding price of permits equals 46 US$/tC. In comparison with the scenario CARTEL, the market supply of permits under the Nash competition is increased by 40 MtC and the price of permits is reduced by 20 US$/tC. The profits are US$ 4.4 bn for FSU and US$ 3.1 bn for EEC in the Nash equilibrium. Summing over the costs of meeting the revised Kyoto targets minus the profits of FSU and EEC leads to the total remaining Annex 1 compliance cost of US$ 2.6 bn. In comparison with that of US$ 4.8 bn under CARTEL, this total compliance cost under NASH is almost cut in half.

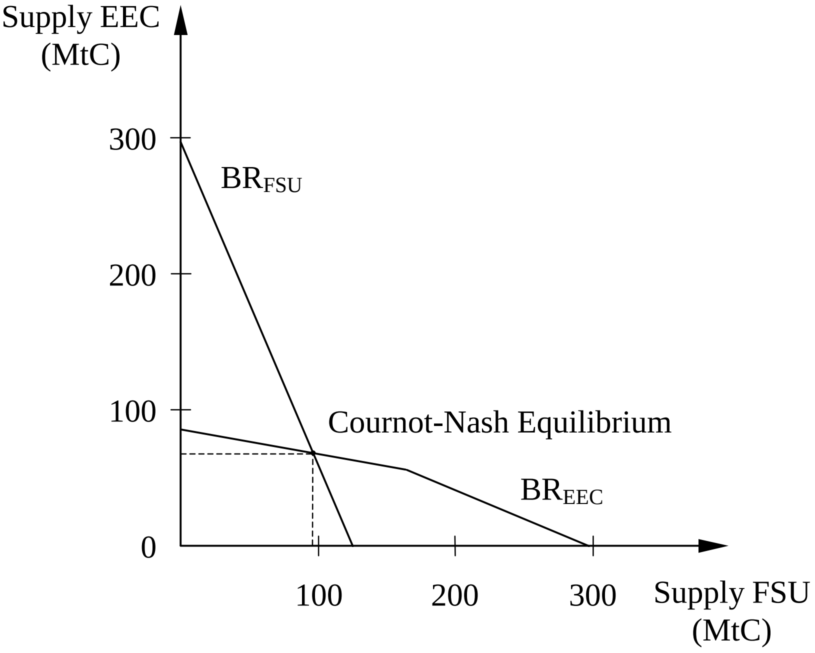

Figure 4.4 EEC and FSU as a Cournot duopoly

4.6.5 MONOP – Only FSU Exercises Monopoly Power

Under the last imperfect competition scenario, only FSU is assumed to exercise market power, while EEC is assumed to be a price taker on the permit market. This assumption seems realistic given the dominant position of Russia and the Ukraine on the supply side of the international emissions trading market. The small supplier EEC is then treated as a competitive fringe and follows the price leadership of the dominant region FSU. In this case, FSU knows how much EEC supplies at any given price and adjusts the residual demand curve accordingly. Acting as a monopoly, FSU supplies 102 MtC at a price of 36 US$/tC. The maximum monopolistic profit of FSU is reduced to US$ 3.6 bn from US$ 4.4 bn US$$_{95}$ under NASH and 4.8 bn US$$_{95}$ under CARTEL. The fringe supplier EEC delivers 86 MtC to the market and gets a profit of US$$_{95}$ 2.6 bn (US$$_{95}$ 3.1 bn revenues from sales less US$$_{95}$ 0.5 bn costs of abatement) in comparison with US$$_{95}$ 3.1 bn under NASH and US$$_{95}$ 3.5 bn under CARTEL. The total volume of permits traded between the hot air suppliers and the other Annex 1 regions increases to 188 MtC from 126 MtC under CARTEL and 166 MtC under NASH. The total costs of all remaining Kyoto-constrained Annex 1 regions meeting the Kyoto abatement requirements are reduced to US$$_{95}$ 8.4 bn: US$$_{95}$ 0.9 bn for AUN, US$$_{95}$ 1.0 bn for CAN, US$$_{95}$ 4.6 bn for EUR and US$$_{95}$ 1.9 bn for JPN.

Table 4.3 summarizes the results of the different policy simulations undertaken, and Figure 4.5 illustrates these quantitative results. Our results show that there is ample space for non-competitive supply behavior under Annex 1 emissions trading. Without the US participation, the residual excess demand of all remaining Kyoto-constrained Annex 1 regions is given by the curve D which is obtained by adding up the potentially demanded and supplied quantities at each market price as described in Section 4.4. Under competitive Annex 1 emissions trading $TRD_{/US}$, FSU and EEC supply hot air in excess of market demand. If FSU and EEC together exercise monopoly power (CARTEL), they sell hot air permits until the marginal revenues of permit sales (MR) are equal to the marginal costs of abatement, which are zero. If only FSU exercises monopoly power and EEC is treated as a fringe supplier (MONOP), FSU perceives the excess permit demand curve $D_{/EEC}$. FSU sells hot air until the marginal revenues of permit sales ($MR_{/EEC}$) equal zero. As indicated in Figure 4.5, the market equilibrium under Nash lies just between the CARTEL and the MONOP solutions on the excess market demand curve D. Clearly, the supply restrictions imposed as a result of different degree of monopoly power on the permit market all result in, to some extent, an increase in the international permit price and real emission reduction. With the US participation, the excess demand curve faced by the suppliers FSU and EEC with supply curve S is depicted by the curve D_{US}. In this case, the competitive permit market equilibrium is given by TRD_{US}.

Table 4.3 Implications of the non-competitive supply behavior for permits market, compliance costs and environmental effectiveness in 2010

	NTR	TRD w/o US	TRD w/t US	CARTEL	NASH	MONOP
Absolute cost of compliance (bn US$)						
AUN	1.5	0	1.0	1.3	1.0	0.9
CAN	2.6	0	1.1	1.6	1.2	1.0
EEC	0	0	– 3.1	– 3.5 [f]	– 3.1	– 2.6
EUR	9.0	0	5.1	7.1	5.6	4.6
FSU	0	0	– 14.4	– 4.8 [f]	– 4.4	– 3.6
JPN	5.1	0	2.1	3.1	2.3	1.9
Total w/o US	18.2	0	–	4.8	2.6	2.1
USA	31.3	–	15.9	–	–	–
Total w/t US	49.5	–	7.7	–	–	–
Relative cost of compliance (% of business-as-usual GDP in 2010)						
AUN	0.22	0	0.14	0.19	0.15	0.13
CAN	0.27	0	0.12	0.16	0.12	0.10
EEC	0	0	– 0.51	– 0.57 [f]	– 0.52	– 0.44
EUR	0.08	0	0.04	0.06	0.05	0.04
FSU	0	0	– 1.66	– 0.55 [f]	– 0.51	– 0.42
JPN	0.11	0	0.04	0.07	0.05	0.04
Total w/o US	0.09	0	–	0.02	0.01	0.01
USA	0.24	–	0.12	–	–	–
Total w/t US [e]	0.15	–	0.02	–	–	–
Absolute real emission reduction (MtC)						
AUN	33.7	0	17.2	24.0	18.6	15.6
CAN	32.5	0	10.6	15.1	11.5	9.6
EEC	0	0	33.1	0	13.7	30.1
EUR	167.9	0	73.2	104.1	79.6	66.4
FSU	0	0	97.3	0	0	0
JPN	64.0	0	20.4	29.3	22.3	18.5
Total w/o US	298.0	0	–	172.4	145.6	140.2
USA	513.8	–	208.1	–	–	–
Total w/t US	811.8	–	459.9	–	–	–

Table 4.3 continued

	NTR	TRD w/o US	TRD w/t US	CARTEL	NASH	MONOP
Relative real emission reduction (% from business-as-usual in 2010)						
AUN	25.9	0	13.2	18.4	14.3	12.0
CAN	19.7	0	6.4	9.1	7.0	5.8
EEC	0	0	15.8	0	6.6	14.4
EUR	16.1	0	7.0	10.0	7.7	6.4
FSU	0	0	16.4	0	0	0
JPN	19.3	0	6.2	8.8	6.7	5.6
Total w/o US	7.0	0	–	4.0	3.4	3.3
USA	28.4	–	11.5	–	–	–
Total w/t US	19.0	–	10.8	–	–	–
Amount of hot air emitted into the atmosphere (MtC)						
Total w/o US	0	298.0	–	125.6	152.4	157.8
Total w/t US	0	–	351.9	–	–	–
Market price (US$/tC)						
	–[c]	0	40.7	65.9	45.6	35.6
Market size (MtC)						
	–[c]	298.0	482.2	125.6	166.0	188.1
Permit trade (MtC)[d]						
AUN	–	33.7	16.6	9.7	15.1	18.1
CAN	–	32.5	21.8	17.4	20.9	22.8
EEC	–	·[e]	– 89.4	·[e]	– 70.0	– 86.4
EUR	–	167.9	94.7	63.8	88.3	101.5
FSU	–	·[e]	– 392.8	·[e]	– 96.0	– 101.8
JPN	–	64.0	43.5	34.7	41.7	45.5
USA	–	–	305.6	–	–	–

[a] Percentage change with respect to aggregate Annex 1 business-as-usual GDP in 2010.

[b] Percentage change with respect to total Annex 1 baseline emissions in 2010 including the US emissions.

[c] Autarkic marginal abatement costs are 108 US$/tC for AUN, 190 US$/tC for CAN, 127 US$/tC for EUR, 187 US$/tC for JPN and 148 US$/tC for USA.

[d] Positive values indicate permit imports, negative values indicate permit exports.

[e] Permit exports by EEC and FSU are undetermined. Under TRD w/o US total permit supply is 298 MTC, while the corresponding figure under CARTEL equals 126 MtC.

[f] If cartel profits are split up following the egalitarian solution.

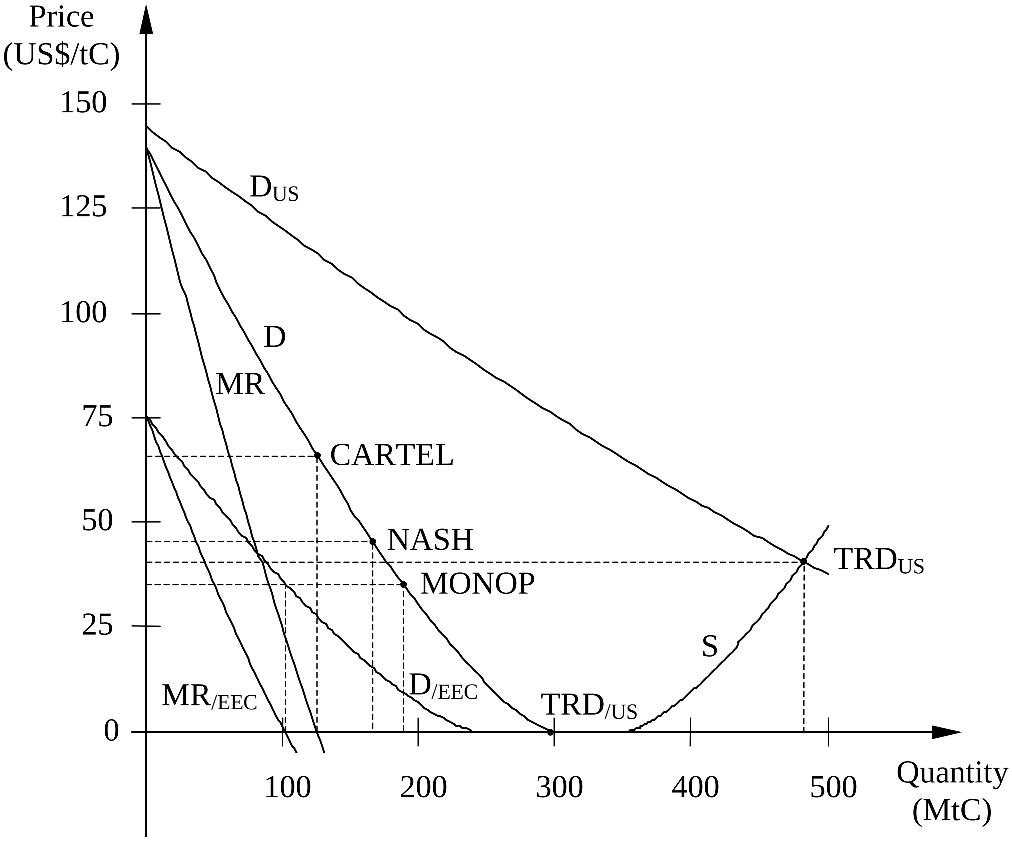

Figure 4.5 Graphical illustration of the results

4.7 Sensitivity Analysis

The parameters of the regional marginal abatement cost curves α and β, which are used in the present chapter, have been estimated using data generated by the world energy system model POLES. To test how sensitive our results are to these parameter values, we conduct a crude Monte Carlo simulation. We assume uniform distributions for each regional parameters α and β. The minimum and maximum possible values are 90% and 110% of the parameters' median values adopted in our preceding analysis, respectively. Other things being equal, the higher (lower) the values of these parameters α and β the higher (lower) the marginal abatement costs associated with a specific amount of abatement: a 10% increase (reduction) approximately doubles (halves) the marginal abatement costs. This in turn leads to a higher (lower) residual excess demand faced by the permit suppliers EEC and FSU. Accordingly, international permit prices and compliance costs for permit importers are pushed up (down) under all the trading scenarios examined. In our Monte Carlo simulation, we draw a value at random from the distribution of each input parameter, and calculate the corresponding results. We repeat this process 1000 times to produce a random sample from the probability distribution over the outputs induced by the uniform distribution over the inputs.

Figure 4.6 shows the relative frequency distribution over international permit prices under the three non-competitive permit supply scenarios examined in our preceding analysis. As would be expected, the international permit price is lowest under MONOP and highest under CARTEL, with the corresponding price under NASH in between. This has been the case in all 1000 simulation runs, although the distribution of permit prices overlaps under different simulation runs (namely, the permit price under MONOP in one run could be higher than that under CARTEL in another run). While the structure of the results does not change, the absolute values of the simulation outputs do as the input parameters change. Measured as the interquartile range between the 0.25 and 0.75 fractiles, a useful measure of the dispersion of the distributions, the international permit prices are in the range of [29 US$/tC, 39 US$/tC] under MONOP, [36 US$/tC, 52 US$/tC] under NASH and [51 US$/tC, 76 US$/tC] under CARTEL, respectively. The reason for the higher degree of uncertainty on the international permit prices under the last two scenarios is that, similar (given the modest degree of non-linearity in the relevant parts of the residual excess demand curves) relative variations (namely inward or outward) in the residual excess permit demand curves translate into larger absolute changes in the price of permits when FSU perceives the excess permit demand curve D rather than $D_{/EEC}$. However, in comparison with the magnitude of the assumed change in marginal abatement costs in the Monte Carlo simulation, the variability of the results seems relatively modest. In addition, the mean sample values, of which the locations are indicated on all three curves with a solid point, are very close to the results derived from the adopted median values in the preceding analysis: 34.5 US$/tC under MONOP, 44.8 US$/tC under NASH and 64.9 US$/tC under CARTEL. Table 4.4 summarizes the descriptive statistics (mean and standard deviation) of the Monte Carlo sample for absolute compliance costs and absolute real emission reduction as well as permit market prices under the three non-competitive permit supply scenarios. It can be seen that these findings also hold for the simulation results of absolute compliance costs and absolute real emission reduction in Section 4.6.

Table 4.4 Descriptive statistics from the Monte Carlo simulation

	CARTEL		NASH		MONOP	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Absolute cost of compliance (bn US$)						
AUN	1.2	0.2	1.0	0.2	0.8	0.1
CAN	1.5	0.3	1.1	0.2	0.9	0.2
EEC	– 3.5 *	0.9	– 3.1	0.7	– 2.5	0.5
EUR	7.1	1.9	5.5	1.3	4.5	0.9
FSU	– 4.7 *	1.0	– 4.3	0.9	– 3.5	0.6
JPN	3.0	0.6	2.3	0.5	1.8	0.3
Absolute real emission reduction (MtC)						
AUN	24.3	5.8	18.8	4.1	15.7	3.2
CAN	15.1	3.5	11.5	2.5	9.6	1.8
EEC	0	0	13.2	1.8	30.3	5.9
EUR	102.8	10.6	78.6	7.8	65.6	8.2
FSU	0	0	0	0	0	0
JPN	29.4	7.1	22.3	5.0	18.4	3.8
Market price (US$/tC)						
	64.9	15.9	44.8	10.1	34.6	6.6

* If cartel profits are split up following the egalitarian solution.

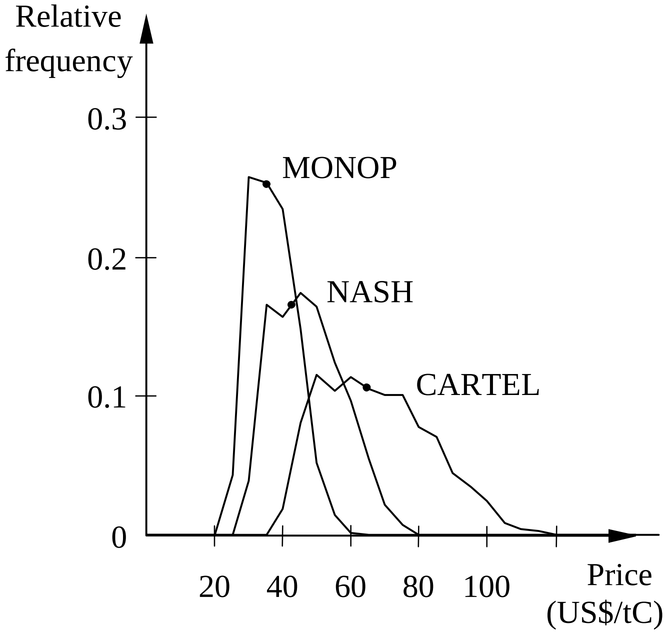

Figure 4.6 Relative frequency distributions over market prices of permits

4.8 Conclusions

Given the small number of permit sellers on international permit markets, this chapter has illustrated how market power could be exerted under Annex 1 trading in the absence of the US ratification and taking account of sinks credits as agreed in Bonn and Marrakech. It has explored the potential implications of the non-competitive supply behavior for the international market of tradable permits, compliance costs for the remaining Annex 1 countries to meet their revised Kyoto targets, and the environmental effectiveness.

As the largest carbon emitter in the world, the US withdrawal from the Kyoto Protocol has had by far the greatest impact on the environmental effectiveness of the Protocol. This would lead to no real emission reduction in any of the remaining Annex 1 regions, whereas the ratification of all Annex 1 regions, including the US, would result in the real emission reduction of 812 MtC or 19.0% below the total Annex 1 baseline emissions in 2010 (if trading across Annex 1 countries were not allowed) and of 460 MtC or 10.8% below the total Annex 1 baseline emissions in 2010 (if trading across Annex 1 countries were allowed). As the biggest single buyer on the international market of tradable permits, the absence of the US ratification would significantly reduce the demand for permits. As a consequence, the price of permits under Annex 1 trading would drop from US$ 40.7 per ton of carbon with US ratification to zero without the US ratification. All remaining Kyoto-constrained Annex 1 countries could benefit from the excess supply of hot air from FSU and EEC and meet their Kyoto targets at zero costs. But seller countries would lose all their revenues under perfect Annex 1 trading.

Given FSU and EEC as the dominant suppliers of emissions permits on the international market, it is certainly not in their interest to sell excess emissions permits at zero price. Instead, they may exert market power to maximize their revenues from selling permits. Our results show that such supply restrictions by exploiting market power results in substantial economic losses for all remaining Kyoto-constrained Annex 1 regions in comparison with the case of perfectly competitive supply, while it generates substantial financial flows to FSU. Depending on how market power is exerted under Annex 1 trading, the overall compliance costs of all remaining Annex 1 regions in the case where FSU and EEC form a sellers' cartel (CARTEL) could reach as much as two times that in the case where only FSU acts as a monopoly (MONOP). But no matter how market power is exerted under Annex 1 trading, all

Kyoto-constrained Annex 1 regions are better off with emissions trading in terms of their compliance costs than with no trading at all. Moreover, curtailing permit supply by market power will cut the amount of hot air being emitted into the atmosphere by more than half and at the same time, increases Annex 1 domestic abatement efforts. Thus, the overall environmental effectiveness is increased in comparison with the case of perfectly competitive supply, although real emissions reductions are much less effective under the market power scenarios examined here than in the case of the ratification of all Annex 1 regions including the US. A Monte Carlo analysis reveals the uncertainties associated with our results, but supports the robustness of our qualitative as well as quantitative findings.

There are several aspects that warrant further investigation. First, our analysis focuses on the first commitment period, and does not consider the possibility of banking of permits. It is conceivable that a low price in the first commitment period will induce sellers to defer portion of their emissions permits for use in subsequent periods (Manne and Richels, 2001). Such a flexibility is particularly attractive if sellers expect much higher prices of permits in the subsequent periods due to a further tightening of emissions targets, reentry of the US to the Kyoto Protocol, and higher compliance costs encountered by themselves as their economies are expected to begin recovering in the subsequent commitment periods. Second, our analysis is based on a partial equilibrium framework, ignoring other potential effects of non-competitive supply behavior, notably the potential negative terms-of-trade consequences.[35] Thus, it would be interesting to identify the sources of the differences between the partial equilibrium results and the respective general equilibrium results, and to quantify their significance.

It should be pointed out that our analysis only examines the issue of market power on the supply side under Annex 1 trading. Some analysts suggest considering the possibility of expanding emissions trading to include developing countries via CDM to diminish FSU and EEC's ability to exercise market power. Incorporating developing countries into an international emissions trading scheme not only increases the number of market participants,

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[35] For example, monopolistic pricing on the international permits market influences the prices and quantities of other goods traded internationally. Such effects are transmitted through the trade channels to other trading partners. The resulting feedback effects on the monopolist, for example Russia, who is dependent heavily on oil and gas exports, are that it could lose in relative terms from setting higher permit prices through its negative impact on international oil and gas prices. Based on general equilibrium models, earlier studies on compliance with the original Kyoto emissions targets (e.g., Bernstein et al., 1999; Burniaux, 1998; MacCracken et al., 1999) have assessed such potential effects of market power.

but also makes more cheap permits available. Both effects reduce FSU and EEC’s ability to exert market power. But the point is that the US withdrawal leaves plenty of excess hot air of zero costs. This will substantially reduce incentives to invest in CDM projects that imply reduced financial flows channeled to developing countries through CDM. Thus, developing countries might not oppose such a supply side cartelization so that they can benefit from the corresponding high price of permits. After all, their certified emission reductions from CDM projects, although less costly than the equivalent amount of abatement undertaken within Annex 1 purchasing countries, are not made available at zero costs. Some OECD countries, particularly those more concerned about the environmental effectiveness of the Kyoto Protocol, would also not necessarily interfere with such a move, as it would compel the remaining Kyoto-constrained Annex 1 countries to undertake otherwise very little domestic abatement actions and at the same time, would still reduce their costs of compliance.

Appendix 4.A The Original Kyoto GHG Emission Reduction Targets and the Revised Targets under the Bonn Agreement and the Marrakech Accords

Table 4.5 Reduction targets under the Bonn Agreement and the Marrakech Accords

	Label[a]	Target w/o sinks[b]	Sinks credits[c]	Targets w/t sinks[d]
Australia	AUN	108	2.7	110.7
Austria	EUR	87	4.0	91
Belgium	EUR	92.5	1.1	93.6
Bulgaria	EEC	92	2.1	94.1
Canada	CAN	94	11.2	105.2
Czech Republic	EEC	92	1.6	93.6
Denmark	EUR	79	1.2	80.2
Estonia	EEC	92	1.9	93.9
Finland	EUR	100	1.8	101.8
France	EUR	100	1.6	101.6
Germany	EUR	79	1.4	80.4
Greece	EUR	125	1.3	126.3
Hungary	EEC	94	2.2	96.2
Iceland	EUR	110	8.0	118
Ireland	EUR	113	1.4	114.4
Italy	EUR	93.5	1.1	94.6
Japan	JPN	94	4.9	98.9
Latvia	EEC	92	2.9	94.9
Liechtenstein	EUR	92	15.1	107.1
Lithuania	EEC	92	3.0	95
Luxembourg	EUR	72	1.4	79.4
Monaco	EUR	92	1.0	93
Netherlands	EUR	94	1.0	95
New Zealand	AUN	100	2.0	102
Norway	EUR	101	3.8	104.8
Poland	EEC	94	1.7	95.7
Portugal	EUR	127	2.2	129.2
Romania	EEC	92	2.8	94.8

Table 4.5 continued

Russian Federation	FSU	100	5.0	105
Slovakia	EEC	92	3.5	95.5
Slovenia	EEC	92	7.9	99.9
Spain	EUR	115	1.8	116.8
Sweden	EUR	104	4.0	108
Switzerland	EUR	92	4.5	96.5
Ukraine	FSU	100	1.4	101.4
United Kingdom	EUR	87.5	1.3	88.8
United States	USA	93	3.3	96.3

[a] Label used to correspond to those Annex 1 countries covered in each aggregate region modeled.

[b] As % of 1990 GHG emissions (UNFCCC, 1997).

[c] Total allowed sink credits agreed in Bonn Agreement and the Marrakech as % of 1990 GHG emissions (Nemry, 2001).

[d] As % of 1990 GHG emissions.

Appendix 4.B Model Description

This section provides the mathematical description of the marginal abatement costs-based, partial equilibrium model for emissions trading underlying the simulations set up in Section 4.5. We begin with the model formulation for a competitive system of permit trade without the occurrence of hot air. Second, we show how hot air can be accounted for (i.e. the scenario TRADE). Finally, we lay out the set-up for the case of non-competitive permit supply behavior. The model for the scenarios CARTEL and MONOP is described first. Finally, the model set-up for the scenario NASH is specified. It should be pointed out that even though we have a mathematical expression for each country's marginal abatement cost curve, we can not simply deduce our results analytically. The reason is that it is not possible to derive an expression for the residual market demand curve for permits. Thus, we have to rely on our simulations where we are just adding up the quantities potentially demanded at each price across all remaining Kyoto-constraint regions.

4.B1 Competitive permit trading

Under competitive permit trading, all countries *i* are price takers. Each country minimizes its compliance costs to some exogenous target level $k_{i.}$ Compliance costs equal the sum of abatement costs and the costs of buying carbon permits; in the case of permit sales, the second term becomes negative, which means that the country minimizes the cost of abatement minus the income from selling permits. Costs are minimized subject to the constraint that a country meets its exogenous reduction target, in other words: a country's initial endowment of permits plus the amount of permits traded on the market (q_i, $q_i > 0$ if permits are bought, $q_i < 0$ if permits are sold) on the market may not exceed the emission target level k_i:

$$\min_{q_i, e_i} C_i\left(\overline{e_i} - e_i\right) + P \cdot q_i \qquad (4.B1)$$

$$s.t. \quad e_i = k_i + q_i\,,$$

where

C_i denotes the abatement cost function for reducing carbon emissions,

$\overline{e_i}$ stands for the business-as-usual emissions,

e_i are the actual emissions, and

P is the permit price taken as exogenous.

The first order conditions for the cost minimization problem yield:

$$C_i^{'}\left(\overline{e_i} - e_i\right) = P\,. \qquad (4.B2)$$

In the optimum, the price taking countries abate emissions up to a level where their marginal abatement costs (*C'*) equal the permit price. Total costs of reducing emissions to the overall target level $K = \sum_i k_i$ are minimized, since all opportunities for exploiting cost differences in abatement across countries are taken.

4.B2 Competitive Emissions Trading with Hot Air: TRADE

The amount of hot air h_i equals the difference between the emission target and the business-as- usual emissions:

$$h_i = k_i - \overline{e_i} \ . \tag{4.B3}$$

For countries with hot air – in our case EEC and FSU - the emission target exceeds the business-as- usual emissions ($h_i > 0$). For all other countries in the model $h_i = 0$. A hot air country is always selling permits. It minimizes costs of abatement minus income from selling permits ($q_i - h_i$, $q_i < 0$)[36]:

$$\min_{q_i, e_i} C_i \left(h_i + \overline{e_i} - e_i \right) + P \cdot q_i \tag{4.B4}$$

$$s.t. \quad e_i = k_i + q_i - h_i \ .$$

The first order conditions yield:

$$C_i^{'} \left(h_i + \overline{e_i} - e_i \right) = P \ . \tag{4.B5}$$

The existence of hot air does not change the cost-efficiency property of unrestricted competitive permit trading since marginal abatement costs are still equalized. However, hot air sold on the permit market does not imply any effective (real) emission reduction in the hot air countries. The occurrence of traded hot air, therefore, results in an increase of overall emission compared to a situation without international permit trade.

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[36] Hot air countries supply their hot air amounts at any permit price. The total supply of permits from hot air countries is $q_i - h_i$.

4.B3 Non-Competitive Permit Supply Behavior

CARTEL and MONOP

Monopolistic permit supply is assumed under the scenarios CARTEL and MONOP. It is characterized as a situation in which one region (denoted ‘*m*’) has supply power on the permit market while all other countries, denoted as fringe ‘*f* ’, behave as price takers. The monopoly region under the scenario CARTEL consists of the coordinating hot air regions EEC and FSU, while it is only FSU under the scenario MONOP. In the latter case, EEC is assumed to be part of the fringe. The fringe countries minimize their compliance costs given the permit price set by the monopolist. They emit carbon until the marginal costs of abatement equal the permit price:

$$C_f{}'\left(h_f + \overline{e_f} - e_f\right) = P\,. \tag{4.B5’}$$

The aggregate permit demand of the fringe, which is in total a net importer of permits, is:

$$Q_F\left(P\right) = \sum_f q_f\left(P\right). \tag{4.B6}$$

The monopolist sets its permit supply (q_m<0) and actual emissions e_m to minimize abatement costs minus income from permit sales:

$$\begin{aligned} &\min_{q_m, e_m} C_m\left(h_m + \overline{e_m} - e_m\right) + P \cdot q_m \\ &\text{s.t. } e_m = k_m + q_m - h_m \\ &\qquad P = P\left(Q_F\right) \end{aligned} \tag{4.B7}$$

where *P* is the inverse demand function of the fringe countries. The first order conditions of the cost minimization problem indicate that the monopolist sets marginal abatement costs equal to marginal revenue:

$$C_m'\left(h_m+\overline{e_m}-e_m\right)=P-P'\left(Q_F\right)\cdot q_m\,. \tag{4.B8}$$

Comparing (4.B5’) with Equation (4.B8), we see that marginal abatement costs are not equalized between the fringe countries and the monopolist, thus resulting in overall efficiency losses due to market power.

NASH

Under the scenario NASH it is assumed that hot air countries EEC and FSU set simultaneously their quantity supplied to the permit market given one region’ beliefs about the action taken by its rival. Each region, denoted ‘*n*’, sets its permit supply q_n and actual emissions e_n to minimize abatement costs minus income from permit sales given the choice of permit supply by the other region, denoted ‘-*n*’:

$$\begin{aligned}&\min_{q_n,e_n}\; C_n\left(h_n+\overline{e_n}-e_n\right)+P\cdot q_n \\ &s.t.\quad e_n=k_n+q_n-h_n \\ &\qquad\;\; P=P\left(Q_F-\overline{q_{-n}}\right),\end{aligned} \tag{4.B9}$$

where P is the inverse demand function of the fringe countries from (4.B6) taking into account the other region’s permit supply $\left(q_{-n}\right)$. The first order condition for the cost minimization problem yields:

$$C_n'\left(h_n+\overline{e_n}-e_n\right)=P-P'\left(Q_F-\overline{q_{-n}}\right)\cdot q_n\,, \tag{4.B10}$$

resulting in the best-response (or reaction) function for the region *n* (BR_n). The best-response function for the region –*n* (BR_{-n}) can be derived accordingly. A Nash equilibrium corresponds to the intersection of the best response functions of EEC and FSU.

5 Efficiency Gains through Joint Implementation [*]

5.1 Introduction

In order to promote international climate policies, Germany has already committed itself to substantial unilateral emission reductions in the early 1990s: The German government set a carbon emission reduction target of 25 percent in 2005 as compared to 1990 emission levels which has been reconfirmed several times since then. Concerns on adverse employment effects of carbon emission constraints for the national economy have induced policy makers to adopt an environmental tax reform as a key instrument for meeting the reduction target. Such a reform entails an increase in environmental taxes together with a revenue-neutral reduction in labor costs. This policy is supposed to yield a double dividend in the simultaneous reduction of harmful greenhouse gas emissions (first dividend) and alleviation of unemployment problems (second dividend). However, while the environmental dividend is generally beyond controversy, the employment dividend is not. 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 in addition new distortions in intermediate and final consumption. The negative impacts on labor demand by levying additional environmental taxes (tax interaction effect) may dominate the positive impacts of using additional revenues for cuts in labor costs (revenue recycling effect). Theoretical and empirical results show that the prospect for the second dividend crucially

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[*] This chapter is based on the papers ‘Joint Implementation as a Flexible Instrument – A CGE Analysis between a Developing and an Industrialized Country’, with C. Böhringer and K. Conrad, in: J. Albrecht (ed.), *Instruments for climate policy: Limited versus unlimited flexibility*, Cheltenham (UK), Northampton, MA (USA): Edward Elgar (New Horizons in Environmental Economics), 2002, 148-169; and ‘Carbon Taxes and Joint Implementation - An Applied General Equilibrium Analysis for Germany and India’, with C. Böhringer and K. Conrad, in *Environmental and Resource Economics*, 24 (1), 49-76, 2003

depends on the existing inefficiencies of the tax system, labor market imperfections and the level of environmental taxes (i.e. the environmental target).[37]

The levying as well as the recycling of environmental taxes induce substitution and output effects. Under a higher emission or energy tax, employment benefits from a positive substitution effect of labor for energy. However, there is also a negative output effect due to increased prices and reduced domestic demand. The output effect could outweigh the substitution effect on labor demand. Given the latter, a policy which achieves an environmental goal with a weak negative output effect by reducing the level of environmental taxes and strengthening domestic demand is therefore of interest.

At the strictly domestic level, using lower environmental taxes to ameliorate negative effects on production activities and labor demand would directly trade off with higher emissions. Germany would then fall short of its stated reduction target. Yet, international treaties on climate protection allow for the supplementary use of flexible instruments to exploit cheaper emission reduction possibilities elsewhere. The concept of joint implementation has been incorporated into the Kyoto Protocol to the UN Framework Convention on Climate Change (UNFCCC, 1997).[38] Instead of meeting its reduction target solely by domestic action, Germany could enter joint implementation with developing countries such as India, where Germany buys part of its emission reduction from abroad.[39]

In our analysis below, we investigate whether an environmental tax reform *cum* joint implementation (JI) provides employment and overall efficiency gains as compared to an environmental tax reform *stand-alone* (ETR). We address this question in the framework of a large-scale computable general equilibrium (CGE) model for Germany and India where Germany may undertake joint implementation with the Indian electricity sector. Our main finding is that joint implementation largely offsets the adverse effects of carbon emission constraints on the German economy. Whereas strictly domestic action by Germany (i.e. ETR) implies a loss in economic performance and employment, JI reduces substantially the welfare losses and provides employment gains. JI significantly lowers the level of carbon taxes in

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[37] For a survey on the double-dividend literature see Goulder (1995b) and Bovenberg (1997).

[38] Under Articel 6, countries with emission reduction targets (Annex I countries) may fund joint implementation projects in other Annex I countries in return for ‘emission reduction units’, which may be supplemental to domestic actions for the purpose of meeting the commitments. Articel 12 defines the Clean Development Mechanism (CDM) as joint implementation between Annex I and non-Annex I countries. In the following, we only refer to joint implementation as the general concept.

[39] For detailed information on joint implementation see Kuik et al. (1994), Jackson (1995) and Jepma (1995).

Germany and thus reduces the total costs of abatement as well as negative effects on labor demand. In addition, JI triggers direct investment demand for energy efficient power plants produced in Germany. This provides positive employment effects and additional income for Germany. For India, joint implementation equips its electricity industry with scarce capital goods leading to a more efficient power production with lower electricity prices for the economy and substantial welfare gains.

There have been several studies on the economic and environmental effects of green tax reforms for Germany based on numerical large-scale models and real data (e.g. Conrad and Wang, 1993; DIW, 1994; Buttermann and Hillebrand, 1996; Böhringer et al., 1997; Bach et al., 2001; Welfens et al., 2001). The evidence on employment and welfare effects is mixed, partly due to differences in the concrete tax reform scenarios considered but more so due to differences in modeling assumptions with respect to existing tax distortions, foreign closure and labor market imperfections. Our analysis complements the existing literature in several ways. From a policy point of view, it does not focus on a narrow discussion of the double-dividend hypothesis but investigates how flexibility through JI could improve the prospects for efficiency and employment gains from environmental tax reforms in Germany. From a methodological point of view, we provide an innovative application of the cost or productivity gap concept by Jorgenson and Nishimizu (1978): The effects of JI are evaluated taking into account efficiency improvements in developing countries through capital transfers.

The remainder of this chapter is organized as follows. Section 5.2 lays out the generic model structure complemented with extensions for representing joint implementation and measuring productivity changes. Section 5.3 describes the policy scenarios and reports our simulation results. Section 5.4 entails our conclusions and lines of future research.

5.2 Analytical Framework

This section presents the main characteristics of a comparative-static multi-sector CGE model for the German and Indian economies. The general equilibrium approach provides a consistent and comprehensive framework for studying price-dependent interactions between the energy system and the rest of the economy. This is important since carbon abatement policies not only cause direct adjustments on fossil fuel markets but also produce indirect spillovers to other markets which in turn feed back to the economy. Therefore, computable general equilibrium 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 (Weyant, 1999).

As to our concrete model formulation, functional forms and key assumptions are standard to the CGE approach to carbon abatement policy analysis (see Chapter 2) except for the representation of productivity gaps in the electricity sector (see Section 5.2.3). In the following, we provide a non-technical model overview. Appendix 5.A contains an algebraic model summary.

5.2.1 Basic Model

The choice of production sectors and the nesting of functional forms captures key dimensions in the analysis of greenhouse gas abatement such as differences in carbon intensities and the scope for substitutability across energy goods and carbon-intensive non-energy goods. The energy goods identified in the model are coal (COL), natural gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). The non-energy sectors include important carbon-intensive industries such as transportation services (TRN) and an aggregate energy-intensive sector (EIS). The rest of the production side is divided into other machinery (OME), construction (CNS) and other manufactures and services (Y). Primary factors include labor, capital and fossil-fuel resources. Labor is treated as intersectorally mobile within each region, but cannot move between regions. Capital is sector specific and internationally immobile. A sector-specific resource is used in the production of primary fossil fuels (crude oil, coal and gas), resulting in upward sloping supply schedules for those goods. Table 5.1 summarizes the sectors, countries and primary factors incorporated in the model.

Table 5.1 Overview of sectors, factors and countries

Sectors		Primary factors		Countries	
COL	Coal	CAP	Capital	GER	Germany
CRU	Crude oil	LAB	Labor	IND	India
GAS	Natural gas	RES	Sector-specific resource		
OIL	Refined oil products				
ELE	Electricity				
EIS	Energy-intensive sectors				
TRN	Transport equipment				
OME	Other machinery				
CNS	Construction				
Y	Manufactures and services				

5.2.1.1 Production

Nested constant elasticity of substitution (CES) cost functions are employed to specify the substitution possibilities in domestic production between capital (K), labor (L), energy (E) and material (M) intermediate inputs.

In the production of commodities other than primary fossil fuels and electricity, intermediate non-energy goods and crude oil (used as feedstock) are employed in fixed proportions with an aggregate of energy, capital and labor at the top level. At the second level, a CES function describes the substitution possibilities between labor and the aggregate of capital and the energy composite. At the third level, capital and the energy composite trade off with a constant elasticity of substitution. The energy aggregate is, in turn, a nested CES composite of electricity and primary energy inputs. The primary energy composite is defined as a CES function of coal and a CES aggregate of refined oil and natural gas. In the production of electricity non-energy goods as well as crude oil and refined oil products, which do not constitute fossil fuel options in power generation, enter in fixed proportions with a composite of labor, energy, and capital. The latter is given as a CES function between labor inputs and a restricted CES sub-function of capital and energy. At the lower energy nest, gas and coal inputs trade off with a constant elasticity of substitution. The KLEM nesting structure for production in non-fossil fuel sectors reflects common perception of the substitution possibilities except for the trade-off between capital, labor and energy. Some models (see e.g. Manne and Richels, 1992) specify a trade-off between energy and the value-added aggregate, whereas other models (e.g. Welsch, 1996b) choose the trade-off between labor and an energy-capital composite. The latter disaggregation has been adopted for the current model since it reflects empirical evidence that labor is a similar substitute for both energy and capital (see Burniaux et al., 1992).

In the fossil fuel production activity (crude oil, natural gas and coal), labor, capital and energy inputs enter a CES composite at the lower nest. At the top level, this aggregate trades off with the sector-specific fossil-fuel resource at a constant elasticity of substitution. The latter is calibrated in consistency with empirical price elasticities of fossil fuel supplies.

5.2.1.2 Private demand

Final private demand for goods and services in each region is derived from utility maximization of a representative household subject to a budget constraint. In our comparative-static framework, overall investment demand is fixed at the reference level. Total income of the representative household consists of factor income and transfers. Final demand of the representative agent is given as a CES composite of an energy aggregate and a non-energy consumption composite. Substitution patterns within the energy aggregate and the non-energy consumption bundle are reflected via Cobb-Douglas functions.

5.2.1.3 Government demand

The government distributes transfers and provides a public good (including public investment) which is produced with commodities purchased at market prices. In order to capture the implications of an environmental tax reform on the efficiency of public fund raising, the model incorporates the main features of the German tax system: (linear progressive) income taxes including social insurance contributions, capital taxes (corporate and trade taxes), value-added taxes and other indirect taxes (e.g. mineral oil tax). In all simulations, we impose revenue-neutrality in the sense that the level of public provision is fixed. Subject to this equal-yield constraint, additional revenues from environmental taxes get recycled through cuts in labor costs (social insurance payments). As to India, we do not incorporate details of taxation, but assume that constant public good provision is financed lump-sum by the representative consumer.

5.2.1.4 International trade

All commodities are traded internationally. We adopt the Armington assumption that goods produced in different regions are qualitatively distinct for all commodities. Intermediate as well as final demands are (nested CES) Armington composites of domestic and imported varieties. Germany and India are assumed to be price-takers with respect to the rest of the world (ROW) which is not explicitly represented as a region in the model. Trade with ROW is incorporated via perfectly elastic ROW import-supply and export-demand functions. There is an imposed balance of payment constraint to ensure trade balance between Germany and India on the one hand, with ROW on the other hand. That is, the value of imports from ROW to Germany and India must equal the value of exports from these countries to ROW after including a constant benchmark trade surplus (deficit).[40]

5.2.1.5 Labor market

The analysis of the employment effects associated with an environmental tax reform requires an appropriate specification of unemployment for the German economy. In our formulation, unemployment is generated by the existence of a 'wage curve', which postulates a negative relationship between the real wage rate and the rate of unemployment. The specific wage curve employed (see Appendix 5.B) can be derived from trade union wage models as well as from efficiency wage models (Hutton and Ruocco, 1999). As to India, we assume that labor is in fixed supply and labor markets are perfectly competitive.

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[40] There are different types of macroeconomic closure rules (see, e.g., Dewatripont and Michel, 1987; Kehoe et al., 1995), but no clear cut theoretical justification for the choice of a particular one. Our static model accommodates, e. g., different macroeconomic closure alternatives for the foreign sectors and the government. With respect to the foreign sector closure, we fix the trade deficit with ROW and determine exports and imports endogenously. For the government we assume an endogenous government deficit. The activity level of the government is then fixed. The sensitivity of simulation results to macroeconomic closure rules is analyzed in Rattso (1982) and Kehoe et al. (1995).

5.2.2 Modeling Joint Implementation

The rationale behind joint implementation is the same as with emissions trading: cost-effectiveness requires that measures to limit greenhouse gas emissions should be taken where they are cheapest, i.e. marginal abatement costs should be equalized across different sources. However, as compared to emissions trading, JI is based on concrete projects. The JI donor country receives emission credits that may count towards its own emission targets for carrying out climate protection projects in return for funds and technology given to the JI host. The implementation of project-based JI mechanisms in top-down models where sectoral production possibilities are given by aggregate functional forms raises some difficulties. Instead of using a discrete step-function for the abatement cost curve based on bottom-up estimates, emission abatement possibilities are implicit to the flexible functional form. The challenge is to specify and calibrate the functional form in such a way that it provides a reasonable approximation for the marginal abatement costs available from engineering data. For this purpose we employ flexible CES functions with a rather sophisticated nesting of energy inputs. Energy supply and demand calibration is based on physical energy flows and energy prices (see 5.2.4). In the model, JI is represented as a sectoral permit trade regime where sectors in non-abating countries qualifying for JI – in our case the Indian electricity sector – are endowed with sector-specific emission budgets. The amount of permit rights is set equal to the baseline carbon emissions of the Indian electricity sector. Under JI, the donor - here Germany - will demand emission rights (credits) from the JI host - here the Indian power industry - as long as the price of the emission credit is below its marginal abatement costs at home. On the other hand, the Indian power industry will deliver emission credits to Germany as long as the marginal costs of abating carbon in the power industry are lower than the price or revenue received for the emission credit. According to this arbitrage rule, the Indian electricity sector will allocate its baseline emission rights between credits for Germany and demand for its own domestic production. Without joint implementation, the quantity of available emission rights in German is fixed. Emission credits from joint implementation enlarge the total emission budget of Germany which allows for a reduction of the domestic carbon tax while complying with the overall carbon emission constraint.

The principal JI mechanism underlying our model simulations in Section 5.3 is illustrated in Figure 5.1. The flexibility mechanisms allow a redistribution of the emission reductions between the countries, although the overall target reduction is unchanged. Given the total emission reduction requirement $\overline{A}$ in Germany, only the volume A_G will be achieved by domestic action whereas the remainder A_I will be abated by the Indian power industry.[41] The carbon price under a strictly domestic environmental tax reform P_{ETR}^{CO2} is reduced to P_{JI}^{CO2} with JI. Total efficiency gains from JI are given by the shaded area KLM. Distribution of these gains are determined here via the market solution: The JI donor country receives a net gain NLM which is equal to its savings of abatement costs adjusted for the expenditure of purchasing emission credits. The electricity industry in India receives a net gain KLN which equals the difference between the revenues from the sale of emission credits and its undergone abatement costs.

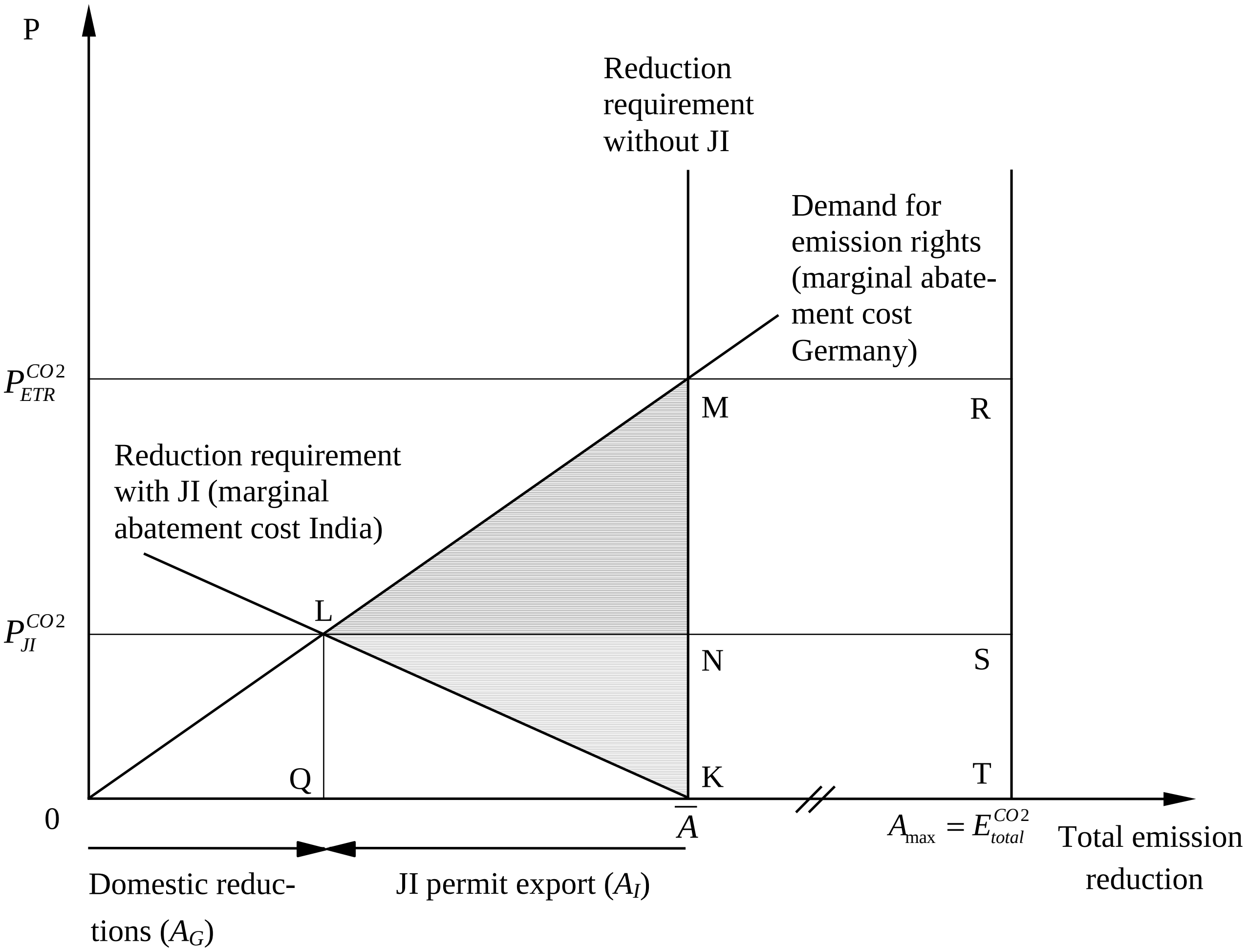

Figure 5.1 Joint Implementation mechanism

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[41] We assume that JI abatement is fully credible towards domestic abatement requirements and that there is no minimum share for domestic abatement. For other specifications see Cansier and Krumm (1996), p. 165.

Reflecting the project character of JI, the electricity industry in India uses the revenues from the sale of emission reductions to buy capital goods directly from Germany. The German capital goods (coal or gas power plants) increase the capital stock in the Indian electricity sector. This direct investment exerts a positive effect on employment in the German manufacturing industries. Additional revenues from permits reduce the electricity price in India. Tax revenue in Germany for reducing non-wage labor cost is the area MKTR before JI. After JI tax revenue is only LQTS where LQKN is the amount of money paid by Germany for emission credits. The area NKTS is now left for reducing non-wage labor costs.

5.2.3 Joint Implementation under Productivity Gaps in the Electricity Producing Industry

Reflecting empirical evidence we assume that there are productivity differences between Germany and India in the electricity sector. Since energy efficiency of fossil fuel fired power plants in Germany is significantly higher than in India, the German industry could invest in Indian power plants to reduce the productivity difference, hereby improving India's energy efficiency. In other words, India’s energy producers use the JI revenues received from Germany for replacement of older inefficient power plants with new highly efficient gas or coal power plants.[42] This results ceteris paribus in a decrease in variable costs or an increase in output.

The cost or productivity gap must be taken into account when assessing joint implementation projects based on capital transfer to improve efficiency. To measure such a cost or productivity gap between the German and the Indian power sector, we employ the measurement of productivity differences as introduced by Jorgenson and Nishimizu (1978). Our approach is similar to the measurement of total factor productivity over time, but will be applied to measure spatial differences. We use the dual concept of measuring a cost gap.

The point of departure is a joint restricted CES sub-cost function in both countries which describes production of the energy-capital aggregate *EK* in the electricity sector from a fossil fuel composite *E* and capital *K:*

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[42] India’s electricity sector is largely in the responsibility of State Electricity Boards (SEBs). Almost all SEBs are making losses and are nearly bankrupt. Therefore the electricity sector in India has been suffering a severe shortfall in investment resources. See Bose and Shukla (1999).

$$C = C(PE, EK, K, D) \tag{5.1}$$

where *PE* is the price of fossil fuel, *EK* the output, *K* the capital stock, and *D* a dummy variable. The restricted cost function incorporates the short-run impact of quasi-fixed inputs' capacity restrictions on total factor productivity (TFP) growth, reflecting a temporary (short-run) equilibrium. Quasi-fixed inputs should then be evaluated at their shadow rather than their rental prices (i.e. the ex-post prices rather than the ex-ante prices) in order to derive accurate measures of TFP (Berndt and Fuss, 1986). We assume the cost function to be linear homogenous in *EK* and *K*. Because output levels, capital stock and the factor price are expressed relative to India, the dummy variable takes on the value 0 for India (*I*) and 1 for Germany (*G*). The dummy variable catches country specific deviations from the joint cost function. It shifts the cost function inwards or outwards. The difference in cost between India and Germany at a given point in time is calculated as the total differential of the cost function in Equation (5.1). In form of logarithmic derivatives, we get:

$$\frac{d \ln C}{d\, D} = s_E \frac{d \ln PE}{d\, D} + \frac{\partial \ln C}{\partial \ln EK}\frac{d \ln EK}{d\, D} + \frac{\partial \ln C}{\partial \ln K}\frac{d \ln K}{d\, D} + \frac{\partial \ln C}{\partial\, D} \tag{5.2}$$

where $s_E = \frac{\partial \ln C}{\partial \ln PE} = \frac{PE \cdot E}{C}$ is the cost share of energy in this aggregate (Shephard's Lemma). In Equation (5.2) the partial derivatives of the variable cost function with respect to the capital stock *K* represents the savings in costs from a marginal increase in the stock. This savings in costs is the shadow price of the capital stock (PK_s). In logarithmic partial derivative with respect to *K*, it is the cost share (multiplied by –1), i.e.:

$$PK_s = -\frac{\partial\, C}{\partial\, K} \quad \text{and} \quad s_K = \frac{PK_s \cdot K}{C} = -\frac{\partial \ln C}{\partial \ln K}\,.$$

Under the additional assumption of profit maximizing supply decisions, we have $PEK = \partial\, C / \partial\, EK$. The logarithmic partial derivative with respect to output then corresponds to the revenue cost-share. By rearranging Equation (5.2), we get:

$$\frac{\partial \ln C}{\partial D} = \frac{d \ln C}{d D} - s_E \frac{d \ln PE}{d D} - \frac{PEK \cdot EK}{C} \frac{d \ln EK}{d D} + s_K \frac{d \ln K}{d D}. \tag{5.3}$$

Equation (5.3) shows the sectoral difference in costs between India and Germany if the costs were adjusted for the differences in the levels of production, capital stock, and factor prices at a given point in time. If there is a disadvantage in costs of an Indian sector, then $\partial \ln C / \partial D$ is negative. The left-hand side means that with given Indian energy price, output *EK* and capital stock *K* in the German industrial environment, cost would be lower. In the production function approach $EK = F(E, K, D)$, the equivalent interpretation is that output would be higher by that percentage if Indian *EK* is produced with Indian *E* and *K* in Germany. Therefore, in Germany the resources are used more efficiently. The cost gap is calculated by adjusting the difference in costs by the weighted differences in *PE*, *EK* and *K*. Since under CRTS of $C(\cdot)$ in *EK* and *K* and under marginal cost pricing $PEK \cdot EK = C + PK_s \cdot K$, or

$$\frac{PEK \cdot EK}{C} - \frac{PK_s \cdot K}{C} = 1$$

we can cast Equation (5.3) into the expression

$$\frac{\partial \ln C}{\partial D} = \frac{d \ln C}{d D} - s_E \frac{d \ln PE}{d D} - \frac{d \ln EK}{d D} - \frac{PK_s \cdot K}{C} \frac{d \ln (EK/K)}{d D}. \tag{5.3'}$$

An increase in capital productivity EK/K in India would lower the positive term $\frac{d \ln (EK/K)}{d D}$ and would therefore reduce the Indian productivity gap.

As a discrete approximation of the Divisia Index in Equation (5.3), we use the Törnquist index. Then the cost gap s_D can be calculated as:

$$\begin{aligned} s_D = {} & \ln C(G) - \ln C(I) - \overline{s}_E \left(\ln PE(G) - \ln PE(I)\right) \\ & - \overline{s}_{EK} \left(\ln EK(G) - \ln EK(I)\right) + \overline{s}_K \left(\ln K(G) - \ln K(I)\right) \end{aligned} \tag{5.4}$$

with $\overline{s}_j = \frac{1}{2}\left(s_j(G) + s_j(I)\right)$ for $j = E, EK, K$.

Regional differences in the cost structure of two industries result from differences in the quantities of inputs which, in turn, are determined by the level of production, by factor prices, and by the capital stock. A descriptive analysis indicates which components are accountable for the differences in costs but does not determine their contribution in explaining the differences in factor demand. Therefore, the causes for the changes in the cost gaps have to be determined by employing an econometric model.

For our CGE analysis, we use a CES specification of the restricted cost function:

$$C = PE \cdot \left[\left(EK \cdot \exp(-a_0 - a_D \cdot D)\right)^{-\rho} - (d_K + d_{K,D} \cdot D) \cdot K^{-\rho}\right]^{-\frac{1}{\rho}} \cdot (d_E + d_{E,D} \cdot D)^{\frac{1}{\rho}} \qquad (5.5)$$

where $\sigma = \frac{1}{1+\rho}$ is the elasticity of substitution. The cost shares s_E, s_{EK}, s_K and the gap $s_D = \frac{\partial \ln C}{\partial D}$ can be derived by differentiating the cost function with respect to *PE*, *EK*, *K* and *D*.[43] It is

$$s_D = \frac{\partial \ln C}{\partial D} = \frac{-a_D + \frac{d_{K,D}}{\rho}\left(\frac{EK}{K}\right)^{\rho} \exp(-a_0 \cdot \rho)}{1 - \left(\frac{EK}{K}\right)^{\rho} \exp(-a_0 \cdot \rho) \cdot d_K} + \frac{d_{E,D}}{\rho \cdot d_E} \qquad (5.6)$$

and $\frac{\partial s_D}{\partial \left(\frac{EK}{K}\right)} > 0$ gives the impact of $\frac{EK}{K}$ on the difference in costs. The positive sign means that the difference in costs ($s_D < 0$) will be reduced if capital productivity can be raised in India.

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[43] See Appendix 5.C for the calibration of the parameters under a temporary equilibrium and a cost gap.

The following figure (Figure 5.2) presents the situation. We assume that output is the same in both countries and that the relative price of energy with respect to capital is normalized to be one in both countries in a long run equilibrium situation. Given capital shortage in India, the shadow price of capital, PK_s, in India is higher than in Germany, implying the less steep slope of the iso-cost line for India in its temporary equilibrium. Since capital is quasi-fixed, India does not produce at its minimal cost combination B. It has to produce at A with $\bar{K}$ = 3, E = 12.5. If India would produce EK = 10 with 4.5 units of capital instead of its 3 units, it would save 3 units of energy (9.5 instead of 12.5). If it would use only 4 units of energy, it would require about 3 times as much capital than Germany. Since the Indian electricity industry is in a short-run equilibrium (*A*), investment in capital through joint implementation would help to reach the long-run equilibrium in *B*. Since energy and capital are internationally traded goods, we assume that the slope of the iso-cost line in *B* and *C* is the same for India's and Germany's electricity sector. Since costs are lower in *B* compared to *A*, the cost gap will be reduced by becoming less negative. From the production side, the saving in costs can be used to buy more inputs and the increase in the resulting output will reduce the productivity gap. In the cost gap calculation in Equation (5.4) $\ln C(I)$ declines, the new s_D^{JI} will be less negative. Therefore the parameter a_0 in the Equation (5.6) for s_D has to be revised.[44] Its new value enters into the variable cost function and thereby into the price determination of *PEK*. Since for electricity the demand side determines the size of the aggregate *EK* (electricity can not be stored), only a CGE calculation can say whether capital productivity EK/K has changed. In a partial equilibrium framework, EK/K will not change if *K* changes because *EK* then changes by the same magnitude, due to constant returns to scale.

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[44] If policy instruments are to be considered to close the gap, then instruments like research and development or infrastructure have to be introduced as arguments into the cost function.

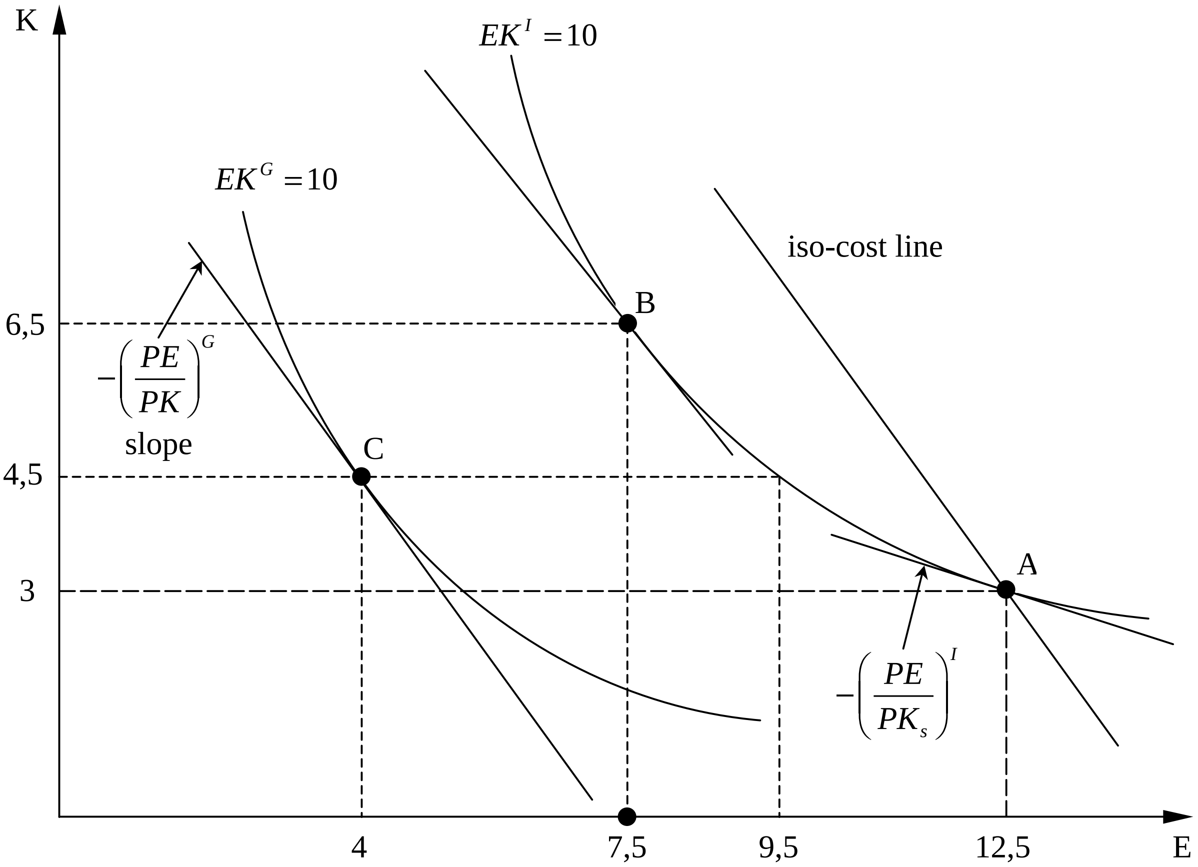

Figure 5.2 Productivity gaps in the electricity sector

5.2.4 Parameterization

Benchmark data are used to calibrate parameters of the functional forms from a given set of quantities, prices and elasticities. Data from two different sources are combined to yield a consistent benchmark data set for 1995:

- *GTAP4* (McDougall et al., 1998). GTAP includes detailed input-output tables for 50 sectors and 45 regions with bilateral trade flows for 1995.
- *IEA energy balances and energy prices/taxes* (IEA, 1996). IEA provides statistics on physical energy flows and energy prices for industrial and household demands.

We accommodate a consistent representation of energy markets in physical units by replacing GTAP’s aggregate input-output monetary values for energy supply and demand with physical energy flows and energy prices as given in IEA’s energy statistics. This ‘bottom-up’ calibration of energy demands and supplies yields sector-specific and energy-specific CO_2 coefficients. The advantage is that marginal abatement cost curves, and hence the cost evaluation of emission constraints, are based on actual energy flows rather than on aggregate monetary data, which strengthens the credibility of the quantitative results. The magnitude of efficiency gains from JI depend crucially on the emission structure in the Indian and German economy.

5.3 Scenarios and Results

Within the EU burden sharing agreement under the Kyoto Protocol, Germany is obligated to reduce its greenhouse gas emissions by 21 % during the period 2008-2012 as compared to its 1990 emission level (EC, 1999b). Independent of this international commitment, the German government adopted a much more ambitious national climate policy plan which foresees a reduction of domestic carbon emissions by 25 % in 2005 vis-à-vis the emission level in 1990. In our simulations, we refer to the 25% reduction target and apply it to our benchmark situation for 1995.[45]

We distinguish two alternative policy scenarios how Germany can meet its reduction target. The first scenario ETR refers to an environmental tax reform in Germany where carbon taxes are levied in order to meet the domestic emission constraint. Carbon taxes are recycled in a revenue-neutral way to lower labor costs. The second scenario JI allows for joint implementation with the Indian electricity sector. Germany's reduction target can be met by domestic abatement as well as emission reduction undertaken in the Indian power sector. Table 5.2 summarizes the implications of the two different abatement scenarios for inframarginal welfare (measured in terms of Hicksian-equivalent variation), unemployment and marginal abatement costs.

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[45] To avoid speculation on the future economic development and baseline emissions for Germany (see e.g. Böhringer et al., 2000a), we abstain from the forward-calibration of the 1995 economy to 2005.

Table 5.2 Welfare, unemployment, marginal abatement cost, emission reductions

	ETR	JI
Welfare in Germany [a]	-0.47	-0.26
Welfare in India [a]	-	2.49
Unemployment in Germany [a]	0.22	-0.49
Marginal Abatement Cost [b]	61	33
Emission reduction in Germany [c]	242	154
Emission reduction in Indian electricity sector [c]	-	88

[a] Percentage change.
[b] In USD_{95} per ton of CO_2.
[c] In mio. tons CO_2.

5.3.1 Welfare

An environmental tax reform *stand-alone* is far more costly for Germany than carbon taxes supplemented with joint implementation. Under ETR a carbon tax of roughly 60 USD is required to cut down Germany's carbon emissions by 25 per cent. With JI the carbon tax can be reduced to about 30 USD while ensuring the same overall environmental effectiveness. Lower domestic abatement efforts reduce costly reallocation of resources towards less carbon-intensive production (see Table 5.3 for the sectoral effects on production).[46] Except for direct efficiency gains from joint abatement under JI, Germany benefits from demand for energy-efficient power plants which triggers additional income. Whereas ETR induces welfare costs of roughly 0.5 per cent, JI offsets largely these adverse effects of carbon emission constraints. As expected, India is not affected by ETR undertaken in Germany. With JI, however, India experiences a large increase in welfare (almost 2.5 per cent). The latter stems from the substantial productivity increase in electricity production due to the capital stock augmentation through JI.

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[46] Coal production in India only decreases by 2.3 % even though coal inputs into power generation under JI decline by 28 % to accommodate the substantial cutback in carbon emissions in this sector. The reason is that the reduced coal demand in the electricity sector leads to a substantial fall in the output price of coal which, in turn, increases coal demand in other sectors. This also explains the ‘sectoral leakage’ effect described below. In addition, the large decrease in the market price of coal by about 40 % exerts a strong cost pressure which results in the dismissal of 26 % of the labor force in coal production.

Table 5.3 Sectoral effects on production and employment (% change)

	GER		IND
	ETR	JI	JI
Production			
COL	-32.31	-20.96	-2.32
GAS	-4.22	-3.21	1.83
OIL	-4.76	-2.58	0.33
ELE	-4.95	-2.76	18.24
EIS	-3.11	-1.69	6.38
TRN	-0.06	-0.03	3.03
OME	0.69	0.50	2.65
CNS	-0.11	0.07	0.52
Y	-0.44	-0.18	1.22
Employment			
COL	-52.90	-38.67	-26.02
GAS	-6.98	-5.33	13.62
OIL	-6.66	-3.67	3.16
ELE	-0.43	-0.19	9.63
EIS	-1.86	-0.99	1.61
TRN	0.20	0.11	-0.87
OME	0.87	0.62	0.21
CNS	-0.03	0.12	-2.20
Y	-0.05	0.05	0.13

5.3.2 Unemployment

Our simulations indicate that higher carbon taxes as necessary under ETR are not likely to yield an employment double dividend given the initial tax distortions and labor market imperfections in Germany. Carbon tax revenues under ETR amount to nearly 45 bill. USD which accommodates a reduction in labor costs of about 5 per cent. The implied positive substitution effects get, however, more than offset by negative output effects due to higher energy prices. JI reduces the negative impact of carbon abatement on employment in Germany. With JI, carbon taxes are reduced and carbon tax revenues fall to 27 billion USD.

As a consequence, labor costs can be lowered by only 3 percent which weakens the substitution effect in favor of labor. On the other hand, the negative output effect is reduced as well - with positive implications for labor demand. In addition, there are direct positive effects on output demand and employment associated with investment under JI.

5.3.3 Emissions

Under ETR Germany must cut down emissions from 972 mio. tons CO_2 to 730 mio. tons CO_2. Entering JI with India, Germany's emissions rise to 818 mio. tons CO_2. In other words, India takes over carbon abatement of 88 mio. tons CO_2 as emissions in the Indian electricity sector decline from 353 mio. tons to 265 mio. tons CO_2. Germany then only fulfills 64 per cent of its national reduction target domestically - the remaining 36 percent is delivered by abatement measures in the Indian power sector. It should be noted, that JI only considers emission abatement in the Indian power sector, i.e. indirect (general equilibrium) effects on emissions by other sectors of the Indian economy are not taken into account. In fact, there is intersectoral carbon leakage for India since increased overall economic activity triggered by JI leads to a rise in carbon emissions of the non-electric production sectors. The ‘intersectoral’ leakage rate, which can be measured as the ratio between the emission increase in the non-electric sectors over emission reduction in power generation, amounts to 56 %. From the point of view of global environmental effectiveness, these non-negligible leakage effects of JI should be taken into account although - in political practice - severe problems with respect to the proper determination of the macro-baseline might occur.

5.3.4 Cost Gap Reduction

Through joint implementation the capital stock in the Indian electricity sector increases by about 14 percent. The reduction in costs due to the movement of the temporary equilibrium towards the long-run equilibrium (which is characterized by less energy and more capital input) results in a significant decline of the electricity price in India. The zero profit condition for the Indian electricity sector states:

$$PELE \cdot ELE = C(ELE; PE, PK, PL) + AC\left(A^I\right) - A^I \cdot P^{CO2} .$$

The costs of abating CO_2 $\left(AC\left(A^I\right)\right)$ are added to the cost of production and the revenues from selling permits at the permit price P^{CO2} are subtracted. Since the revenue is higher than the cost of abatement, the resulting profit (see the area *LNK* in Figure 5.1) can be used to lower the price *PELE* of electricity. Although the price *PE* of fossil fuel increases by the price of a permit (see Table 5.4), the price index of electricity in India declines significantly from 1 to 0.72. As the fossil fuel mix of India has higher CO_2 emission coefficients, the price *PE* in India is higher than this price in Germany. Energy intensity *E/K* drops from 0.40 to 0.27 for India and from 0.33 to 0.26 for Germany. Capital productivity *EK/K* increases from 1.19 to 1.22 for India and decrease from 1.33 to 1.25 for Germany. Overall, *JI* improves the performance of the Indian economy and narrows the productivity gap in the Indian electricity sector with respect to the German sector. The initial gap s_D = -0.67 is reduced to s_D^{JI} = -0.11 with JI.

Table 5.4 Effects of JI on the electricity sector

	Benchmark		JI	
	IND	GER	IND	GER
K (in bill. USD)	1,46	2,39	1,68	2,39
PK	1.44	1	1.15	0.99
E (in bill. USD)	0,58	0,79	0,45	0,63
PE	1	1	2.15	1.58
EK (in bill. USD)	1,73	3,18	2,05	2,99
PEK	1.55	1	1.41	1.12
PELE	1	1	0.72	1.05

5.4 Conclusions

Carbon taxes which are sufficiently high to achieve substantial domestic emission reductions would have non-negligible adverse impacts on welfare and employment in Germany. JI can help to reduce these negative effects through the associated cost savings and additional investment demand from JI host countries. There are, however, some important remarks on the representation of JI in our analytical framework: Planning and implementation of JI projects in a developing country like India typically involve considerable control and transaction costs. These costs may reduce the attractiveness of JI. In our analysis we have neglected this aspect, mainly because of a lack in accurate data. In addition, investments in emission reduction projects in developing countries are risky (see Chapter 6). We also did not consider the problem that JI between Annex I and non-Annex I countries provides an incentive for the parties to overstate baseline emission levels in order to generate additional emission rights. Furthermore, our analysis is restricted to carbon emission constraints for *one* industrialized country, Germany, that can be met through purely domestic action or via joint implementation with *one* developing country, India. A broader setting, which allows for the incorporation of emission constraints on several industrialized countries as well as joint implementation with all developing countries (as foreseen under the Kyoto Protocol) may affect our quantitative results: For example, a larger reduction of global fossil fuel demand by the industrialized world will depress international fossil fuel prices which provides substantial terms-of-trade gains for fuel importers and terms-of-trade losses for fuel exporters. Likewise, the demand and supply schedule for joint implementation projects will be affected by the increased number of participating countries. However, the key mechanisms of JI elaborated in our paper apply independently of such a more general setting.

The implications of our results for ongoing negotiations may be important. Many developing countries have reservations about joint implementation which might be considered as a pre-stage of binding international emission reduction objectives for the developing world. Moreover, some developing countries regard compensation projects as a cheap buy-out option for the industrialized world from their historic obligation to reduce greenhouse gas emissions. However, JI may be the only possibility for developing countries like India to equip its electricity industry with scarce capital goods yielding large welfare gains through more efficient power production and lower electricity prices. As to future research, an intertemporal analysis of the process of capital accumulation in developing countries towards the long-run equilibrium would be desirable in order to shed more light on the dynamic aspects of joint implementation.

Appendix 5.A Algebraic Model Summary

This appendix provides an algebraic summary of the equilibrium conditions for the comparative-static model without unemployment (see Section 2.3 for a description of the basic model). Table 5.A1 explains the notations for variables and parameters. Key elasticities are summarized in Table 5.A2. For the sake of transparency, we do not write down the explicit functional forms but instead use the acronyms CET (constant elasticity of transformation), CES (constant elasticity of substitution), CD (Cobb-Douglas) and LT (Leontief) to indicate the class of functional form in place.

Zero profit conditions

Production of goods except fossil fuels and electricity:

$$\Pi_i^Y = CET\left(PFX_i, P_i\right) - LT\left[PA_{n,n\in N}^Y, PA_{CRU}^Y, CES\left(PL, CES\left(PK_i, PE_i\right)\right)\right] \geq 0,\ \forall i \in V \quad (5.A1)$$

Production of fossil fuels:

$$\Pi_i^Y = CET\left(PFX_i, P_i\right) - CES\left[PR_i, LT\left(PA_{j,j\in I}^{\mathrm{Y}}, PK_i, PL\right)\right] \leq 0,\ \forall i \in F \quad (5.A2)$$

Production of electricity:

$$\Pi_{ELE}^Y = CET\left(PFX_{ELE}, P_{ELE}\right) - LT\left[PA_{n,n\in N}^Y, PA_{OIL}^Y, CES\left(PL, C\left(PE_{ELE}, K_{ELE}, EK_{ELE}, D\right)\right)\right] \leq 0 \quad (5.A3)$$

Sector-specific energy aggregate:

$$\Pi_i^E = PE_i \text{ - } CES\left[PA_{ELE}^Y, CES\left(PA_{COL}^Y, CES\left(PA_{GAS}^Y, PA_{OIL}^Y\right)\right)\right] \leq 0,\ \forall i \in V$$

$$\Pi_{ELE}^E = PE_{ELE} \text{ - } CES\left(PA_{GAS}^Y, PA_{COL}^Y\right) \leq 0 \quad (5.A4)$$

Armington aggregate:

$$\Pi_{di}^A = PA_i^d \text{ - } CES\left(P_i, PM_i\right) - P^{CO2} a_{di}^{CO2} \leq 0 \quad (5.A5)$$

Aggregate imports across import regions:

$$\Pi_i^{M,r} = PM_i^r - CES\left(P_i^s, PFX\right) \leq 0 \quad (5.A6)$$

Investment:

$$\Pi^{INV} = PINV - LT\left(PA^{INV}_{i,i\in I}\right) \leq 0 \tag{5.A7}$$

Public demand:

$$\Pi^{Z} = PZ - CD\left(PA^{Z}_{n,n\in N}, CES\left(PA^{Z}_{e,e\in E}\right)\right) \leq 0 \tag{5.A8}$$

Household consumption demand:

$$\Pi^{C} = PC - CES\left(CD\left(PA^{C}_{n,n\in N}\right), CD\left(PA^{C}_{e,e\in E}\right)\right) \leq 0 \tag{5.A9}$$

Utility production:

$$\Pi^{U} = PU \text{ - } CES\left(PC, PL\right) \leq 0 \tag{5.A10}$$

Market clearance conditions

Labor:

$$\overline{L} \geq \sum_i Y_i \frac{\partial \Pi^Y_i}{\partial PL} + U \frac{\partial \Pi^U}{\partial PL} \tag{5.A11}$$

Capital:

$$\overline{K_i} \geq Y_i \frac{\partial \Pi^Y_i}{\partial PK_i} \tag{5.A12}$$

Natural resources:

$$\overline{Q}_f \geq Y_f \frac{\partial \Pi^Y_f}{\partial PR_f} \tag{5.A13}$$

Domestic output:

$$Y_i \frac{\partial \Pi^Y_i}{\partial P_i} \geq \sum_d A^d_i \frac{\partial \Pi^A_{di}}{\partial P_i} \tag{5.A14}$$

Sector specific energy aggregate:

$$E_i \ \ge \ Y_i \frac{\partial \Pi_i^Y}{\partial PE_i} \tag{5.A15}$$

Import aggregate:

$$M_i \ \ge \ \sum_d A_i^d \frac{\partial \Pi_{di}^A}{\partial PM_i} \tag{5.A16}$$

Armington aggregate:

$$A_i^Y \ \ge \ \sum_j Y_j \frac{\partial \Pi_j^Y}{\partial PA_i^Y} + INV \frac{\partial \Pi^{INV}}{\partial PA_i^{INV}}, \ A_i^C \ \ge \ C \frac{\partial \Pi^C}{\partial PA_i^C}, \ A_i^Z \ \ \ge \ Z \frac{\partial \Pi^Z}{\partial PA_i^Z} \tag{5.A17}$$

Foreign closure:

$$\sum_r \sum_i PFX \frac{\partial \Pi_i^{Y,r}}{\partial PFX} \cdot Y_i^r \ \ge \ \sum_r \sum_i PFX \frac{\partial \Pi_i^{M,r}}{\partial PFX} M_i^r + \sum_r \overline{B}^r \tag{5.A18}$$

Household consumption:

$$C \cdot PC \ \ge \ PL \cdot \overline{L} + \sum_i PK_i \cdot \overline{K}_i + \sum_f PQ_f \cdot \overline{Q}_f - PINV \cdot \overline{INV} - PC \cdot \overline{B}^r \text{, r = IND} \tag{5.A19}$$

$$C \cdot PC + (\overline{L} - L) \cdot PL \ \ge \ PL \cdot \overline{L} + \sum_i PK_i \cdot \overline{K}_i + \sum_f PQ_f \cdot \overline{Q}_f - PINV \cdot \overline{INV} - PC \cdot \overline{B}^r \text{, r = GER}$$

Government consumption:

$$Z \cdot PZ \ \ge P^{CO2} \cdot \overline{CO2} + \mathit{other\ taxes} \tag{5.A20}$$

Government output:

$$\overline{Z} = Z \tag{5.A21}$$

Investment:

$$\overline{INV} = INV \tag{5.A22}$$

Carbon emissions:

$$\overline{CO2} \geq \sum_{d} \sum_{i} A_i^d a_{di}^{CO2} \tag{5.A23}$$

Representation of Joint Implementation

Market clearance for Armington aggregate with additional investment demand through JI:

$$A_i^Y \geq \sum_{j} Y_j \frac{\partial \Pi_j^Y}{\partial PA_i^Y} + INV \frac{\partial \Pi^{INV}}{\partial PA_i^{INV}} + b_i \cdot EXP \cdot P^{CO2} \tag{5.A17'}$$

(Sectoral) carbon emissions constraints:

$$\overline{CO2} + EXP \geq \sum_{d} \sum_{i} A_i^d a_{di}^{CO2} \text{, r = GER} \tag{5.A23'}$$

$$\overline{CO2}_{ELE} + EXP \geq \sum_{d} A_{ELE}^d a_{d,ELE}^{CO2} \text{, r = IND} \tag{5.A24}$$

Table 5.A1 Sets, activity and price variables, endowments

Sets:	
I, i, j	Sectors and goods
E, e	Energy goods (COL, OIL, GAS and ELE)
N, n	Non energy goods
F, f	Fossil fuels (COL, CRU, GAS)
V, v	Non fossil fuels and electricity
r, s	Regions: GER = Germany, IND = India
d	Demand categories: Y = intermediate, C = hh., Z = gov., INV = investment
Activity variables:	
Y_i	Aggregate production
E_i	Aggregate energy input
M_i	Aggregate imports
A_i^d	Armington aggregate for demand category d

Table 5.A1 continued

Activity variables:	
U	Household utility
C	Private consumption
Z	Government consumption
EXP	JI permit export from India to Germany
Price variables:	
P_i	Output price
PE_i	Price of aggregate energy
PA_i^d	Price of Armington aggregate
PM_i	Price of import aggregate
PU	Utility price index
PC	Price of aggregate household consumption
PZ	Price of government consumption
PL	Wage rate
PK_i	Price of capital services
PQ_f	Rent from natural resource
$PINV$	Price of investment demand
PFX	ROW export and import price
P^{CO2}	Price of carbon permit
Endowments:	
$\overline{L}$	Aggregate labor endowment
$\overline{K}_i$	Aggregate capital endowment
$\overline{Q}_f$	Endowment of natural resource
$\overline{INV}$	Aggregate investment demand
$\overline{B}^r$	Balance of payment surplus
$\overline{CO2}$	Endowment of carbon emission rights (Germany)
$\overline{CO2}_{ELE}$	Endowment of carbon emission rights in the Indian electricity sector
Other parameters	
a_{di}^{CO2}	Carbon coefficient
b_i	Share of JI investment demand directed to sector *i*

Table 5.A2 Selected elasticities

Substitution elasticities in non-fossil fuel production (except electricity)	
Capital-labor-energy vs. intermediates	0
Capital-energy vs. labor	0.3
Capital vs. energy	0.5
Electricity vs. primary energy inputs	0.25
Gas-oil vs. coal	0.5
Gas vs. oil	0.9
Substitution elasticities in electricity production	
Capital-energy vs. labor	0.5
Gas vs. coal	4
Substitution elasticities in final demand	
Energy goods vs. non-energy goods	0.5
Non-energy goods vs. non-energy goods	1
Energy goods vs. energy goods	1
Substitution elasticities in government demand	
Fossil fuels vs. non-fossil fuels	1
Fossil fuels vs. fossil fuels	0.3
Elasticities in international trade (Armington)	
Substitution elasticity imports vs. domestic inputs	2
Substitution elasticity imports vs. domestic inputs for GAS and ELE	0.75
Substitution elasticity imports vs. imports	4
Substitution elasticity imports vs. imports for GAS and ELE	1.5
Transformation elasticity domestic vs. export	2
Supply elasticities	
CRU and GAS production	1
COA production	0.5

Appendix 5.B Labor Market Specification

Unemployment in Germany is generated by the existence of a ‘wage curve’, which postulates a negative relationship between the real wage rate and the rate of unemployment:

$$\frac{PL}{PC} = g(ur),\ g' < 0,$$

with PC the consumer goods price index and $ur \equiv (L^S - L^D)/L^S$, the unemployment rate. The wage curve replaces the labor supply curve (Figure 5.3). Consequently, the equilibrium wage rate *(PL/PC)* lies above the market clearing wage rate *(PL/PC)** leading to benchmark unemployment (L^S–L^D). We use a simple specification of the wage curve as a log-linear equation

$$\log\left(\frac{PL}{PC}\right) = \gamma_0 + \gamma_1 \log(ur) - \log\theta,$$

with γ_0 a positive scale parameter, $\gamma_1 < 0$ the elasticity of the real wage in relation to the unemployment rate and (1 - θ) the tax wedge between the employers’ gross wage costs and the employees’ net wages with $\theta \equiv \frac{1-\tau_w}{1+\tau_L}$. If the household is rationed on the labor market, the budget restriction changes in so far as the actual net wage income is determined by $PL \cdot (1-\tau_W) \cdot L^D$. Welfare effects are also based on enforced leisure consumption.

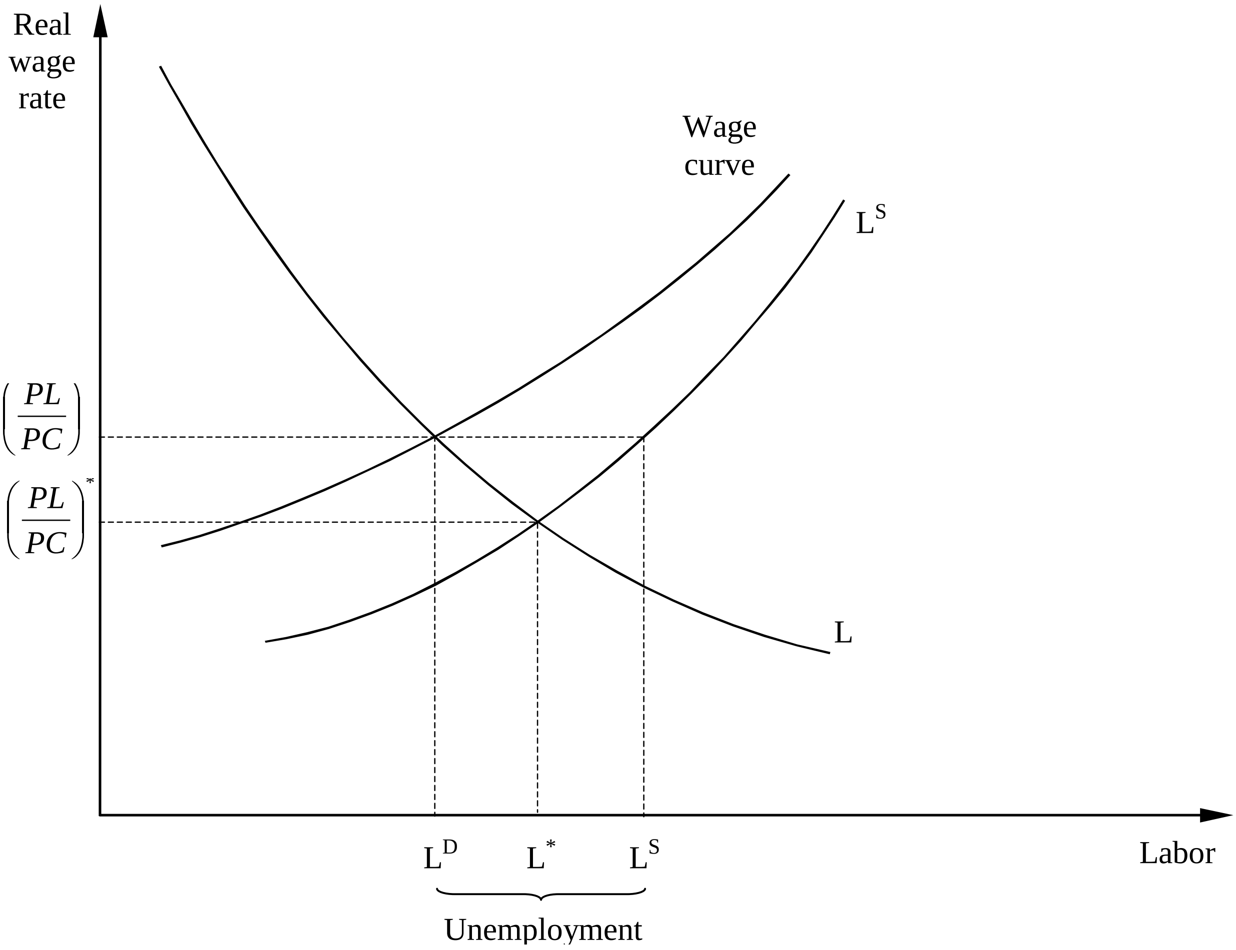

Figure 5.3 Wage curve and equilibrium unemployment

Appendix 5.C Calibration of Parameters under a Temporary Equilibrium and a Cost Gap

In this section the calibration of a joint production function for the electricity producing industry is described, where the Indian sector is in a temporary equilibrium including a productivity gap.

The joint CES production function is:

$$EK = \exp(a_0 + a_D \cdot D) \cdot \left[\left(d_E + d_{E,D} \cdot D \right) \cdot E^{-\rho} + \left(d_K + d_{K,D} \cdot D \right) \cdot K^{-\rho} \right]^{-1/\rho} \qquad (5.C1)$$

where $\sigma = \dfrac{1}{1+\rho}$ is the elasticity of substitution. The cost-minimizing input coefficients are

$$\frac{E}{EK} = \left(d_E + d_{E,D} \cdot D\right)^{\sigma} \left(\frac{PEK}{PE}\right)^{\sigma} \cdot \exp\left[\left(a_0 + a_D \cdot D\right) \cdot \left(-\rho \cdot \sigma\right)\right] \tag{5.C2}$$

$$\frac{K}{EK} = \left(d_K + d_{K,D} \cdot D\right)^{\sigma} \left(\frac{PEK}{PE}\right)^{\sigma} \cdot \exp\left[\left(a_0 + a_D \cdot D\right) \cdot \left(-\rho \cdot \sigma\right)\right] \tag{5.C3}$$

where $(a_0 + a_D) = 0$.

Table 5.C1 Benchmark data for the German electricity sector

K^G (in bill. USD)	2,386
PK^G	1
E^G (in bill. USD)	0,794
PE^G	1
EK^G (in bill. USD)	3,180
PEK^G	1

We start from benchmark data for Germany *(D=1)* (Table 5.C1) and assume $\sigma = 0.5$, i.e. $\rho = 1$. We obtain from Equation (5.C2) and Equation (5.C3):

$$d_E + d_{E,D} = 0.062,\ d_K + d_{K,D} = 0.563. \tag{5.C4}$$

Energy input for India is $E^I = 0.582$. In order to construct a figure for the capital stock, we assume that energy efficiency is lower by 20 percent in India. Since $\left(E/K\right)^G$ is 0.333 in Germany, we assume that $\left(E/K\right)^I = 0.333 \cdot 1.20 = 0.399$ (see Figure 5.4).

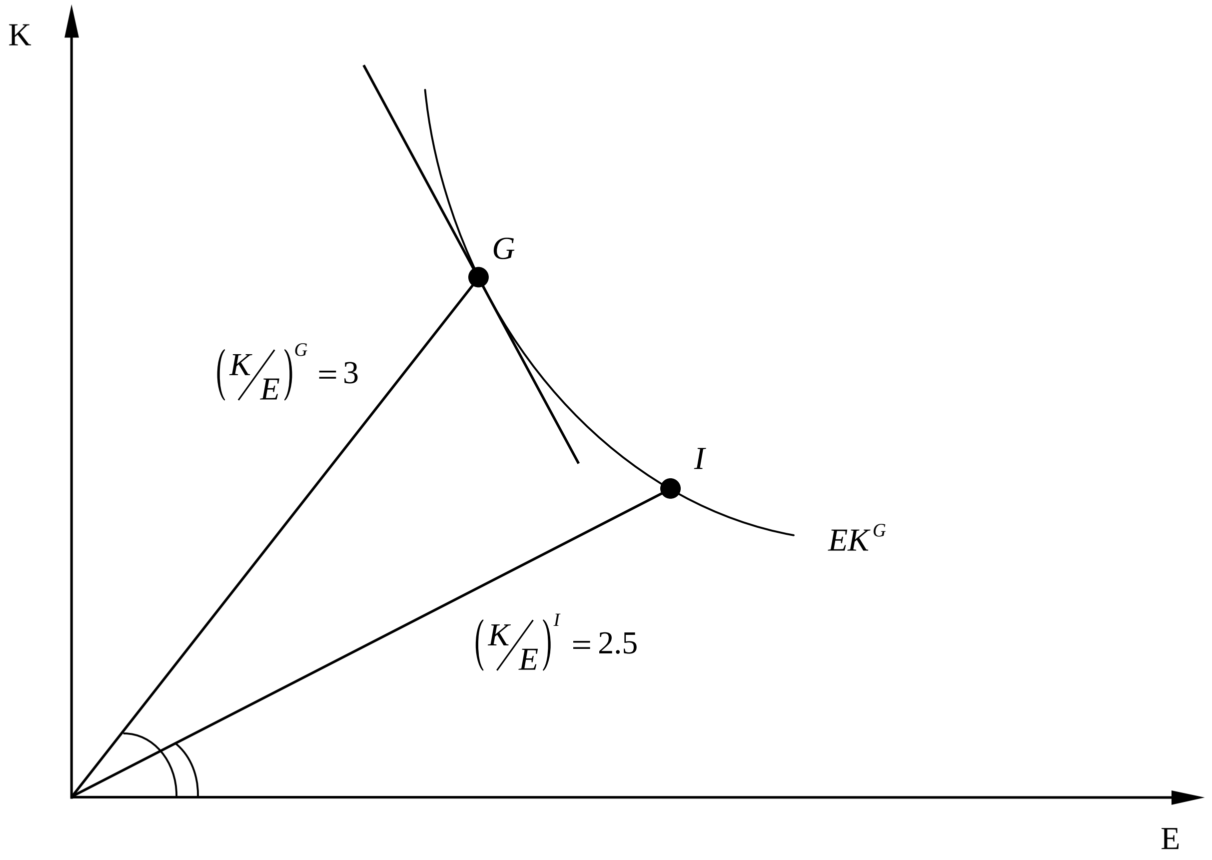

Figure 5.4 Energy efficiency in Germany and India

We assume $PE^I = 1$ which implies a shadow price of capital for India larger than one. For calculating this shadow price *PK* for India we assume that India is in *I* on the isoquant in a temporary equilibrium. From $MRS = \left(PE/PK\right)^I$ we determine PK^I:

$$MRS = \frac{d_E + d_{E,D}}{d_K + d_{K,D}} \left(\frac{K}{E}\right)^{I\,\rho+1} = \left(\frac{PE}{PK}\right)^I \tag{5.C5}$$

Since $\left(E/K\right)^I = 0.399$ and $E^I = 0{,}582$ we obtain $K^I = 1{,}457$ and from Equation (5) $PK^I = 1.44$. We finally assume an efficiency gap of 15 percent, i.e. $EK^I = 0.85\left(K^I + E^I\right) = 1{,}733$. The efficiency term in Equation (5.C1) becomes therefore $\exp(-0.163 + 0.163 \cdot D)$, i.e. $a_0 = -0.163$, $a_D = 0.163$. The productivity gap will be higher than 15 percent because of the temporary equilibrium situation. The price *PEK* comes from the zero profit condition

$$PEK^I \cdot EK^I = PK^I \cdot K^I + PE^I \cdot E^I = 2.681$$

that is, $PEK^I = 1.547$. The data for India are summarized in Table 5.C2.

Table 5.C2 Calibrated benchmark data for the Indian electricity sector

K^I (in bill. USD)	1,457
PK^I	1.440
E^I (in bill. USD)	0,582
PE^I	1
EK^I (in bill. USD)	1,733
PEK^I	1.547

Using these data we can determine d_E and d_K from Equation (5.C2) and Equation (5.C3):

$$d_E = 0.062\,,\ d_K = 0.560$$

and from Equation (5.C4):

$$d_{E,D} = 0.0004\,,\ d_{K,D} = 0.003\,.$$

We can then calculate the productivity gap in terms of the dual cost gaps according to Equation (5.4):

$$s_D = \ln\frac{0.794}{0.582} - \frac{1}{2}\cdot\left(\frac{2.681}{0.582} + \frac{3.180}{0.794}\right)\cdot\ln\frac{3.180}{1.733} + \frac{1}{2}\cdot\left(\frac{2.098}{0.582} + \frac{2.386}{0.794}\right)\cdot\ln\frac{2.386}{1.457} = -0.672$$

In order to derive the variable or restricted cost function *C(PE,EK,K,D)* we insert *E*, derived from Equation (5.C1), into $C = PE \cdot E$ and obtain:

$$C = PE \cdot \left[\left(EK \cdot \exp(-a_0 - a_D \cdot D) \right)^{-\rho} - \left(d_K + d_{K,D} \cdot D \right) \cdot K^{-\rho} \right]^{-1/\rho} \cdot \left(d_E + d_{E,D} \cdot D \right)^{1/\rho}$$

It is

$$PK^I = -\frac{\partial C}{\partial K} = 1.44$$

and

$$s_D = \frac{\partial \ln C}{\partial D} = -\frac{EK^{-\rho} \cdot a_D \exp(a_0 \cdot \rho) - \dfrac{K^{-\rho} \cdot d_{K,D}}{\rho}}{EK^{-\rho} \cdot \exp(a_0 \cdot \rho) - K^{-\rho} \cdot d_K} + \frac{d_{E,D}}{\rho \cdot d_E}. \qquad (5.C6)$$

If $|s_D|$ gets smaller, a_0 in Equation (5.C6) captures this effect and *PEK* from

$$PEK = \frac{C(\cdot)}{EK} + \frac{PK \cdot K}{EK}$$

will decline. If a new gap s_D has been calculated according to the residual method (4), then a_0 follows from Equation (5.C6) by solving it for a_0, with $a_D = -a_0$, since Germany's efficiency is not affected by joint implementation ($a_0 + a_D \cdot D = 0$ for *D* = 1). With joint implementation the gap decreases to $s_D^{JI} = -0.109$ and a_0 becomes $a_0 = -0.038$.

Finally, from profit maximization it is $PEK = \dfrac{\partial C}{\partial EK}$, or, in a revenue share:

$$\frac{PEK \cdot EK}{C} = \frac{EK^{-\rho} \cdot \exp((a_0 + a_D \cdot D) \cdot \rho)}{EK^{-\rho} \cdot \exp((a_0 + a_D \cdot D) \cdot \rho) - (d_K + d_{K,D} \cdot D) \cdot K^{-\rho}} .$$

With German or Indian data, given the calibration, this condition is satisfied. Solved for *EK* it is the supply function which we do not need because demand in the CGE framework will in any case be supplied.

6 Investment Risks in Project-Based Emission Crediting[*]

6.1 Introduction

International climate policy has assigned the leading role in emissions abatement to the industrialized countries who have assumed historical responsibility for the greenhouse gas (GHG) problem. Developing countries remain uncommitted to GHG abatement. They argue that they carry only minor historical responsibility for the increase of global GHG concentrations in the atmosphere. Before decisions are made that could hinder their economic growth through restrictions on fossil fuel use, the industrialized countries should first undertake substantial emission reduction.

This argument, however, is moot. Cooperation between the industrialized and the developing world through joint implementation of GHG emission abatement promises substantial economic gains to both parties. As long as the costs for GHG mitigation that industrialized countries have committed to are lower in developing countries, it makes economic sense that developing countries undertake abatement projects in return for funds from industrialized countries which receive emission credits counting to their domestic emission targets. This basic idea of cost-effectiveness led to the clean development mechanism (CDM) under the Kyoto Protocol accommodating project-based emission reductions in developing countries to exploit the potential for low-cost abatement.

Emission crediting provides market-based incentives to invest in climate-friendly (i.e. emission mitigation) projects since emission reductions can be sold on international permit markets, thus recovering higher initial investment costs. With emission crediting, developing countries could attract larger amounts of foreign direct investment (FDI), which is the

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[*] This chapter is based on the paper ‘Climate Policy Induced Investments in Developing Countries: The Implications of Investment Risks’, with C. Böhringer, *ZEW Discussion Paper* 02-68, Mannheim, 2002.

dominant long-term resource flow to developing countries with a net volume of 185 bn. USD in 1999 (World Bank, 2001). FDI generates technology spillovers, contributes to international trade integration, and fosters human capital formation, all of which accelerates economic growth as the most potent tool for poverty alleviation in developing countries. The importance of FDI as an economic development device is highlighted by the fact that the private flow of FDI overshadows official development assistance (ODA) by a wide margin.[47]

Many policy makers, hence, consider project-based emission reductions as an important instrument to promote sustainable development with respect to improved environmental quality as well as better economic performance of developing countries. Yet, there are concerns that the potential benefits of project-based abatement measures may be substantially reduced by risk concerns of investors associated with abatement projects in developing countries. In addition, the uneven distribution of investment risks and abatement possibilities could produce a (politically undesired) shift in comparative advantage of emission abatement stacked against least-developed countries that typically bear high investment risks and dispose of rather limited abatement possibilities due to low emission levels (Wirl et al., 1998). Climate-friendly investment would then mirror the uneven spread of conventional FDI to developing countries.

The objective of this Chapter is to provide quantitative insights into the relative importance of risk preferences to project-based emission crediting with developing countries. To what extent do risk considerations reduce the potential for cost savings to industrialized countries? What are the implications of risk for the magnitude and distribution of benefits from project-based emission trading among developing countries? So far, quantitative estimates in the literature on the economic impacts of comprehensive emission trading across countries – the so-called ‘where’-flexibility - have been abstracting from risk considerations (see overviews in Weyant, 1999; IPCC, 2001). Based on simulations with a simple partial equilibrium model of emission trade, our key insights can be summarized as follows:

(i) Project-based emission crediting in developing countries drastically reduce the overall costs for industrialized countries that aim at substantial cutbacks of their business-as-usual GHG emission levels. At the same time, it provides considerable income to developing countries with larger low-cost abatement options.

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[47] Official development assistance amounted to only around 41 bn. USD in 1999 (OECD, 2002).

(ii) Incorporation of country-specific investment risks induces only small changes to the magnitude and distribution of benefits from project-based emission trading vis-à-vis a situation where investment risks are absent. Only if investors are highly risk-averse will the differences in risk across developing countries become more pronounced and induce a non-negligible shift in comparative advantage from high-risk developing countries to low-risk developing countries. Although the total amount of emission credits across all developing countries will distinctly shrink for this case (i.e. domestic abatement shares in industrialized countries increase), the low-risk developing countries may attract higher project volumes at the expense of high-risk countries and may also benefit from higher effective prices per emission credit compared to a simulation without risk. The opposite applies to high-risk countries. The welfare implications of risk incorporation for industrialized countries are unambiguously negative.

(iii) Sensitivity analysis with respect to the magnitude of investment risks highlights the relevance of risk aspects. When investors go for high safety of returns and perceive substantial differences in project-based risks across countries, only very cheap projects in high-risk developing countries will be realized, and the associated benefits to high-risk countries may fall close to zero, while low-risk developing countries will fare even better.

The remainder of this Chapter is organized as follows. Section 6.2 describes alternative approaches to capture investment risks. Section 6.3 gives a brief non-technical summary of the partial equilibrium model underlying our simulation analysis, illustrates the potential implications of risk accounting, and describes empirical estimation as well as model implementation of investment risks. Section 6.4 discusses policy scenarios and results. Section 6.5 presents a sensitivity analysis. Section 6.6 concludes.

6.2 Investment Risks in Project-Based Emission Crediting

The clean development mechanism can be characterized as a baseline-and-credit regime under which emission credits for industrialized countries relate to emissions reductions achieved by eligible GHG mitigation projects in developing countries (Sorrell and Skea, 1999; Janssen, 2000). Emission reductions are calculated by comparing the actual emissions of a project with the emissions that would have occurred in the absence of the relevant project, i.e. the reference scenario or baseline. CDM projects involve cross-border investments by industrialized countries in order to generate emission credits for subsequent sale on international credit markets or for transfer emission credits (Grubb et al., 1999). Private investors treat abatement projects in the same manner as ‘conventional’ projects.[48] The investor provides debt and equity financing of the mitigation project in exchange for the claims on the project and the net cash flow it produces (financial return). Emission credits from emission reduction contribute to the net cash flow. Hence, the sale of permits from climate-friendly projects makes it possible to recover higher-investment costs of mitigation projects vis-a-vis ‘conventional’ projects.

The return on the investment is influenced by several factors that can not be controlled by the investor. Drawing on the literature on foreign direct investment, Janssen (2002) distinguishes three main categories of risk that can affect the performance of project-based emissions crediting: (i) *technological risks* that are tied to the process of production and refer to uncertain output quantities; (ii) *economic risks* that refer to uncertain input and output prices; and (iii) *political risks* that arise from uncertainty about property rights on the assets of the revenue streams and involve tax changes or, as the most drastic example, expropriation. Potential investors interested in participating in emissions reduction projects taking place in developing countries may hesitate because of these investment risks. There are high barriers for finding appropriate financing especially for ‘typical’ projects that are small or medium-sized, located in a developing country, and dependent on new or innovative technologies or processes. Further, market prices for emission reductions from climate-friendly investment are uncertain. Finally, risk factors are determined by country specific considerations. Investors will seek host developing countries that are politically and economically stable. In addition, these countries should have a sound institutional framework, a reliable public infrastructure (energy, water, transport) and the capacity to receive and support international investments.[49]

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[48] Investment decisions made by private firms are especially climate-relevant in the building, industrial, transport, and energy sectors. One of the leading infrastructure sectors in attracting private investment is electricity generation, with total private investments of 131 bn. USD between the years 1990 and 1997 (Zhang and Maruyama, 2001).

[49] Instead of building their own diversified portfolio of projects, investors could invest indirectly in a portfolio of projects through investment vehicles offered by financial institutions. One of the few examples for carbon funds is the World Bank’s Prototype Carbon Fund (PCF). Investors in the PCF are private companies such as Gas de France, Deutsche Bank and Mitsubishi, as well as the governments of Canada, Finland, The Netherlands, Norway and Sweden.

Among the developing countries, especially African countries (excluding South Africa) failed to attract inward FDI in recent decades, even though gross returns on investment have been very high. The reasons are the significant risks of capital losses, most importantly macroeconomic instability, loss of assets due to the non-enforceability of contract, and physical destruction caused by armed conflicts (OECD, 2002). Risk diversification by investors may be achieved via investments in different countries, technologies and project types. For our analysis, we assume that the risks in emission crediting are predominantly country-specific, i.e. the variations in the profits of single projects are mainly due to the economic or political conditions in the project's host countries.

Investors invest in 'conventional' projects that yield a return greater than the minimum acceptable hurdle rate, i.e. the return on a risk-free investment plus a risk premium. In contrast, investors will undertake investments induced by domestic emission limitations as long as their perceived return is positive, i.e. the price received for the emission credit sold on international permit markets is higher than the associated (risk adjusted) marginal abatement cost in the project's host country. Below, we first provide the optimal investment rule in the absence of investment risks (Section 6.2.1). We then present different approaches to how risk characteristics can be incorporated, i.e. affect the optimal investment rule (Section 6.2.2).

6.2.1 Emission Crediting in the Absence of Investment Risks

Investors will engage in project-based emission crediting and choose a single risk-free project in country *i* if

$$Y_i = \frac{p - c_i'}{c_i'} > 0, \tag{6.1}$$

where Y_i is the profit per dollar invested in one unit of emission credits, p is the price received for the emission credit and $c_i' = c_i'(q_i)$ are the marginal costs of financing unit abatement in country i, which depends on the quantity of abatement undertaken q_i.

6.2.2 Emission Crediting with Investment Risks

Omission of risk aspects may significantly overestimate the potential benefits from emission crediting. Obviously, investors will demand a higher rate of return, i.e. a risk premium, for risky projects, compared to risk-free options. We capture country-specific risks of emission crediting through a random variable τ_i that quantifies the fraction of the generated credits that drop out. Accounting for country-specific risks, the return from the investment in a single project in country *i* is given by:

$$X_i = \frac{\left(1-\tau_i\right)\cdot p - c_i'}{c_i'} \tag{6.2}$$

where X_i is a random variable, since τ_i is random, with expected monetary value EX_i, variance $V\left(X_i\right)$ and standard deviation σ_{X_i}.[50]

6.2.2.1 Mean-value criterion (μ)

If investors are *risk-neutral* they aim at maximizing their return from abatement investments, disregarding the associated risk levels. Accordingly, they judge risky projects solely by their expected return. The decision rule for abatement investments in a single project becomes

$$EX_i > 0. \tag{6.3}$$

However, investors in unique choice situations usually not only care about the expected return of the investment project but also about the return volatility, which indicates the investment risk. The overwhelming majority of financial models assumes investors to be risk averse, i.e. they have a cautious attitude in the context of reasonable decision making.

The risk aspect of the decision problem does not vanish if we take into account the possibility that project-based emission crediting in country *i* comes about by summing up the

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[50] This holds independent of the responsibility for non-compliance, i.e. under seller beware or buyer beware liability.

incomes of various non-rival subprojects that are carried out at the same time by the investors, i.e. the private companies in industrialized countries or the industrialized countries themselves.[51] However, the bundling of projects in large host countries could significantly reduce the risks of CDM investments and bring them down to the country-specific risks. To this end, carbon funds not only serve as vehicles for channeling investments, but also as risk reduction devices (Janssen, 2002). The risk premia for emission projects may hence be based on risk premia for investment projects in these countries, which we capture through the use of interest rate spreads (see Section 6.3.3).

There are different approaches to manage and control risk. In our empirical assessment we adapt two of them to adjust the investment decision rule and allow for the cost of risk-bearing: the mean-variance (μ-σ) approach which dominates portfolio theory (Markowitz, 1952)[52] and the value at risk (VaR) approach which is a method widely used by banks and financial firms (Jorion, 2001).

6.2.2.2 Mean-variance decision criterion (μ,σ)

Under the mean-variance criteria the investment rule becomes

$$EX_i - \frac{\alpha}{2} \cdot V\left(X_i\right) > 0. \tag{6.4}$$

The mean-variance decision function is consistent with the expected utility principle if the investor's utility function u is of the constant absolute risk aversion (CARA) type and defined over normally distributed monetary consequences X_i. In this case, it is equal to the cash

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[51] The Law of Large Numbers implies that in the case of stochastic independence of the single projects, the average gain converges stochastically towards the expected gain from the single performance as the number of performances approaches infinity. Following this criterion, the choice of a single project may be based on the mean-value criterion in the case of multiple risks. However, the conditions of the Law of Large Numbers are not satisfied in our context, since the number of projects is not sufficiently large and – most importantly - the different projects are not stochastic independent. The part of the variance that is caused by factors that are common to all single projects can not be eliminated by increasing the number of contracts pooled (Sinn, 1989). While technological risks of the individual projects might be considered as stochastically independent, economic and political risks are mostly country specific. The netting-out of dispersions thus does not take place for the country risks.

[52] Portfolio diversification of carbon abatement options as proposed by Springer (2002) requires the assumption of constant marginal abatement costs to derive expected returns from marginal abatement curves. Since this assumption does not seem plausible, we do not follow the portfolio approach.

equivalent of the project return $EX_i - \pi_i$, where π describes the risk premium, i.e. the maximum part of the expected return that the investor is prepared to forfeit in order to avoid the risk associated with the investment.[53]

Empirical findings on risk attitudes are rare and depend to a large extent on the specific method used. Therefore, we study a wide range of values for α, namely $\alpha \in [0;25]$. This range is consistent with studies in financial economics which assume investors with mean-variance preferences and absolute risk aversion (Aït-Sahalia and Brandt, 2001; Alexander and Baptista, 2002). A slightly risk-averse agent may be characterized through $\alpha = 2$, a moderate risk-averse agent through $\alpha = (5, 10)$, and a highly risk-averse agent through $\alpha = 25$.

6.2.2.3 Value at Risk decision criterion (VaR)

Another method to analyze the risk-return trade-off in investments is the Value at Risk (VaR) approach. The concept of VaR as a measure of risk was first proposed by Baumol (1963) and is associated to ‘safety first models’ initially analyzed by Telser (1955). More recently, it became popular in financial economics. For example, the Basel Capital Accord requires internationally active banks to determine the minimum regulatory capital in support of their trading portfolios by using the VaR approach (Santos, 2001).

The VaR indicates the greatest potential loss of a position (or a portfolio) with a stochastic rate of return X_i one expects to suffer over a given time interval within a given confidence level *t* (Jorion, 2001). VaR is usually defined as the dollar loss relative to the mean:

$$VaR_i = EX_i - X_i^*, \tag{6.5}$$

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[53] For small risks, the risk premium can be approximated by $\pi_i = 1/2 \cdot r(EX_i) \cdot V(X_i)$, where $r(x_i) = -u''(x_i)/u'(x_i)$ $\forall x_i$ is the Arrow-Pratt coefficient of (local) absolute risk aversion (ARA) (Pratt, 1964; Arrow, 1965). If the decision maker’s utility function has the form $u(x_i) \sim -e^{-\alpha \cdot x_i}$ (negative-exponential), where ~ denotes equality except for change of utility scale, then the decision maker has constant absolute risk aversion (CARA) with $r(x_i) = \alpha$, i.e. absolute risk aversion is not affected by the level of x_i (Pratt et al., 1995).

where X_i^* is the lowest return at the given confidence level *t* called the sample quantile of the distribution.[54] The decision criterion under the VaR approach is given by:

$$VaR_i = EX_i - \beta \cdot \sigma_{X_i} > 0., \tag{6.6}$$

where in the case of a normal distribution of the return β is such that $\Phi(-\beta) = (1-t)$ with $\Phi(.)$ being the standard normal cumulative distribution function. Without any distributional assumption imposed on the investment return, a useful lower bound on the VaR is provided by Chebyshev's inequality which yields $t = 1-(1/\beta)^2$.[55] For example, the Chebyshev lower bound on the VaR for a confidence level of $t = 0.90$ (0.95) is $EX_i - 3.16 \cdot \sigma_{X_i}$ $\left(EX_i - 4.47 \cdot \sigma_{X_i}\right)$, whereas under normality the VaR is $EX_i - 1.28 \cdot \sigma_{X_i}$ $\left(EX_i - 1.65 \cdot \sigma_{X_i}\right)$ (Alexander and Baptista, 2002).

6.3 Analytical Framework and Parameterization

Below, we first provide a description of the partial equilibrium model of permit trading with investment risk and its parameterization (Section 6.3.1). Section 6.3.2 illustrates the intuition how investment risks change the optimal pattern of abatement across regions. Finally, in Section 6.3.3 we describe how investment risks of CDM projects can be estimated using interest-rate spreads between countries and how investment risks are implemented in our model.

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[54] The probability of a lower value than X_i^* is therefore $(1-t) = P\left(x_i < X_i^*\right) = \int_{-\infty}^{X_i^*} f_{X_i}(x_i)\,dx_i$, with f_{X_i} being the probability density function of the investment return X_i. The computation of the VaR simplifies considerably if the distribution of the return is assumed to be normal. In this case, the problem of finding a VaR is equivalent to finding the deviate β such that the area under the standard normal probability density function to the left of it is (1 - *t*).

[55] The Chebyshev inequality is $P\left\{\left|X_i - EX_i\right| \geq \left(\beta \cdot \sigma_{X_i}\right)\right\} \leq \left[\sigma_{X_i} / \left(\beta \cdot \sigma_{X_i}\right)\right]^2$.

6.3.1 A Model of Permit Trade with Investment Risks

To quantify the economy-wide implications of risk consideration in multilateral emission crediting, we extend the partial equilibrium model for permit trade outlined in Chapter 4. The analysis is based on marginal abatement cost curves for 13 regions. These curves capture the marginal cost of reducing carbon emissions by different amounts within an economy. Marginal costs of abatement may vary considerably across countries due to differences in carbon intensity, initial energy price levels, and the ease of carbon substitution possibilities.

Each country *i*'s compliance costs to some exogenous target level t_i equal the sum of abatement costs, resource costs from investment failure, and the costs of buying carbon permits. The single country's optimization problem can be stated as:

$$\min_{q_i} c_i(q_i) + r_i(q_i) + p \cdot \left(\overline{e_i} - q_i - t_i\right) \qquad (6.7)$$

$$\text{s.t. } q_i \geq 0$$

where q_i are the emission reductions, c_i denotes the abatement cost function for reducing carbon emissions, r_i quantifies the costs from investment risks ($r_i = 0$ for industrialized countries), $\overline{e_i}$ stands for the business-as-usual emissions, t_i denotes the emission target level (i.e. a country's initial endowment of permits), and p is the permit price taken as exogenous. The quantity of permits traded is given by $\overline{e_i} - q_i - t_i$.

The first-order condition for the cost minimization problem is given by:

$$c_i^{'}(q_i) + r_i^{'}(q_i) = p \qquad (6.8)$$

In the optimum, countries abate emissions up to a level where their marginal abatement costs plus marginal investment risk are equal to the permit price. The marginal abatement costs experienced by industrialized countries that demand emission permits from project-based abatement, exceed the marginal abatement costs experienced by developing countries by the amount of the marginal costs from investment risk. Total costs of reducing emissions to the overall target level are minimized, since all opportunities for exploiting cost differences in abatement across countries are taken.

The empirical specification of the costs from investment risks and their concrete implementation for different risk attitudes is described in Section 6.3.3. For the regional marginal abatement costs curves, we adopt a constant elasticity function of the form:

$$c_i^{'}(q_i) = \chi_i \cdot q_i^{\delta_i} \tag{6.9}$$

In order to determine the coefficients χ and δ, we employ a least-square procedure based on a sufficiently large number of discrete observations for marginal abatement costs and the associated emission reduction in each region. These values stem from the world energy system model POLES (Criqui et. al., 1996), which embodies a detailed bottom-up description of regional energy markets and world-energy trade. Table 6.1 summarizes the countries and regions in the model, their baseline emissions in the year 2010[56] and the least-square estimates for the coefficients of marginal abatement cost curves.

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[56] In our comparative-static simulations we employ 2010 as the target year for emission reduction commitments by industrialized countries. The marginal abatement cost curves generated by the POLES model are also based on bottom-up data for 2010.

Table 6.1 Model dimensions and data

Countries and Regions		Emissions [a]	FDI [b]	χ	δ
Industrialized World					
AUN	Australia and New Zealand	130		0.675	1.442
CAN	Canada	165		1.567	1.379
CEA	Central European Associates	209		0.316	1.388
EUR	Europe (EU15 and EFTA)	1,040		0.114	1.369
FSU	Former Soviet Union (incl. Ukraine)	593		0.046	1.482
JPN	Japan	330		0.718	1.338
USA	United States	1,809		0.020	1.427
Developing World					
AFR	Africa	294	7,949	0.366	1.231
ASI	Other Asia	655	18,189	0.295	1.231
CHN	China	1,131	38,753	0.022	1.280
IND	India	351	2,169	0.452	1.201
MPC	Mexico and OPEC	531	1,461	0.546	1.269
MSA	Middle and South America	394	3,893	0.299	1.456

[a] Baseline emissions in MtC in the year 2010 based on DOE (2001) reference case.
[b] Inward FDI flows to developing countries in millions USD in the year 1999 (World Bank, 2001).

6.3.2 Economic Effects of Investment Risks

Figure 6.1 illustrates the central effects of investment risks on the emission credit market in a simple three-country partial equilibrium framework. The effects are similar to those of transaction costs (Stavins, 1995).[57] There is some industrialized country that faces total abatement requirement of *T*. It can fulfill its obligations by either domestic abatement or by investments in abatement projects abroad. The demand curve *D* for emission credits from abroad is determined by the marginal abatement cost curve of the industrialized country. On the other hand, there are two (unrestricted) project host countries with marginal abatement

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[57] Transaction costs in pollution allowance trading may arise from a variety of activities associated with market exchange, e.g. search and information acquisition, bargaining over prices, and negotiation, monitoring and enforcement of contracts (Stavins, 1995). In our analysis we abstract from such transaction costs. Note that investment risks are sometimes considered as transaction costs in a broader use that covers any policy-related costs other than the conventionally measured economic adjustment responses (Krutilla, 1999).

cost functions $c_i^{'}$ (i = 1,2) that yield the total supply *S* of emissions generated through projects.

In the absence of investment risks, the industrialized country demands emission credits generated through projects as long as the price for the credits is below its marginal abatement costs. In the market equilibrium, marginal abatement costs are equalized at price *p* across domestic abatement activities undertaken in the industrialized country and projects abroad that are hosted in the developing countries. The total amount of emission credits generated by projects abroad is $q = q_1 + q_2$, with q_1 representing projects undertaken in country 1 and q_2 projects undertaken in country 2, respectively. In the cost-effective solution, the industrialized country purchases credits *q* and abates domestically $T - q$.

Investment risks are real resource costs and lead to a different equilibrium than in the absence of investment risks, where marginal abatement costs are equalized across all regions in equilibrium. It is still cost effective, but involves greater aggregate compliance costs than the cost-effective solution in the absence of investment risks. If investment risks associated with abatement projects are taken into account as described in (6.3), the investment decision is governed by the risk-adjusted marginal abatement costs $\tilde{c}_i^{'} = \left(1/\left(1-\tau_i\right)\right)\cdot c_i^{'}$, which is the effective permit supply curve facing permit demanders. We assume that only investments in country 2 are risky and induce a shift of its effective supply curve in the investor's perspective from $c_2^{'}$ to $\tilde{c}_2^{'}$. Rather than equilibrating marginal abatement costs as is done in the absence of investment risk, the sum of marginal abatement costs and marginal investment risks are equalized. Investment risks raise the costs for the participants in permit trade and thereby unambiguously decrease the volume of permit trading. The new market equilibrium with investment risks is characterized by a higher credit price $\tilde{p}$ which decreases the purchase of emission credits (i.e. the industrialized country's abatement investments) from abroad to $\tilde{q}$ and increases domestic abatement of the industrialized country to $T - \tilde{q}$. Hence, investment risks abroad shift the comparative advantage to domestic actions. In addition, the amount of investment projects in the more risky country 2 decreases $\left(q_2 - \tilde{q}_2\right)$ while more projects are undertaken in the less risky country 1 $\left(\tilde{q}_1 - q_1\right)$ reflecting a shift in comparative advantage towards the less risky host country.

Overall, the potential efficiency gains from permit trade are reduced under risk accounting vis-à-vis a situation where risk is neglected. The true costs of control are higher with investment risks. This stems partly from the resource costs from investment risks and partly from the suppression of permit trade that has been mutually beneficial in the absence of investment risks. The burden from investment risk considerations is unevenly shared between permit demanders and high- and low-risk permit suppliers. The benefits from emission crediting for the industrialized countries and higher risk host countries decrease, whereas low-risk host countries may gain compared to the 'no-risk' situation. Industrialized countries are unambiguously worse off compared to a situation characterized by the absence of investment risks. The industrialized countries have to do more abatement domestically and pay higher prices on the permit market. The increase in compliance costs for the industrialized country in Figure 6.1 equals the area *EHIR*. It is composed of higher abatement costs (*HIJ*) and higher costs of permit imports (*EHJR*) from both no-risk country 1 (*EFNR*) and high-risk country 2 (*EGLR*). The no-risk host country 2 is unambiguously better off since it enjoys higher profits from permit trade (*EFQR*). The effects of investment risks on risky countries such as country 2 are ambiguous. On the one hand, they profit from higher permit prices (*EGMR*), on the other, hand the trading volume is reduced and they have to bear the resource costs from investment risks (*MK0*). As with the tax incidence, the overall effects depend on the elasiticities of the marginal abatement cost functions, which determine the share of the resource costs from emission crediting that can be passed on to industrialized countries as an increase in the price of permits. In general, the burden from investment risks falls more heavily on the countries with relatively steep marginal abatement cost curves.

Figure 6.1 illustrates the important point that industrialized countries ignoring investment risks of project-based emissions crediting overestimate the potential cost savings from credit trading, i.e. the desirable level of investment abroad, and misallocate investments across project-host countries with different risk levels. High-risk countries receive less investments than in the absence of investment risks, low-risk countries receive more investments.

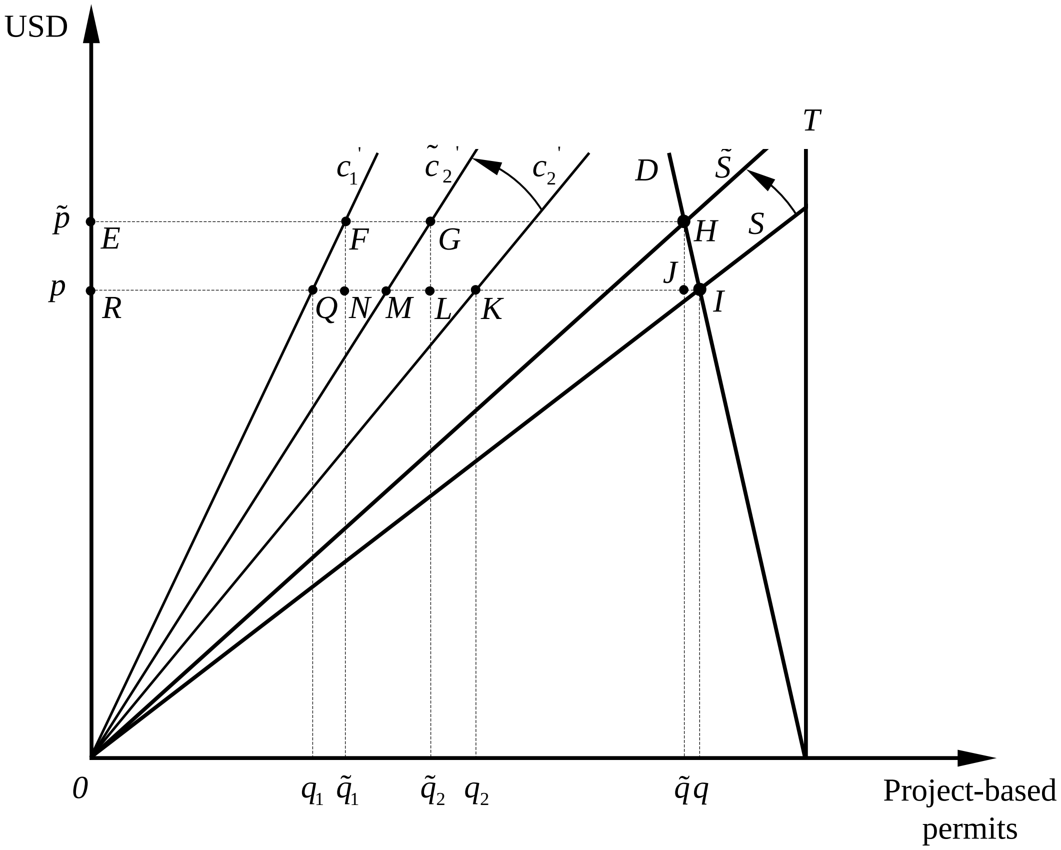

Figure 6.1 Effects of investment risks

6.3.3 Estimation of Investment Risks and Implementation

The default risk premium, i.e. the higher rate of return investors will demand for risky projects compared to risk-free options, reflects the market's assessment of country and project risk. To estimate risk premia at both the country and project level, different techniques may be applied, e.g. econometric analysis of past projects (Dailami and Leipziger, 1999). Saini and Bates (1984) give an overview over various methods for the analysis of country-specific investment risk, which is the predominant risk category in mitigation projects. They hence provide a lower bound estimate of the risk involved in project investment. One indicator of country risks are sovereign debt ratings determined by both political factors (degree of democratization, integration with world economy, security risks) and economic factors (per capita GDP, growth prospect, public debt, price stability, balance of payment flexibility, external debts). These are provided by international rating agencies, such as Standard & Poors

Corporation and Moody's Investors Service.[58] Another established approach is the use of the interest rate spread. Several studies have shown that interest rate spreads between bonds carry substantial information for determining country risk (e.g. Edwards, 1986).

For our analysis, we employ bond yield spreads between long-term government bonds of the developing country *i* where the emission abatement project is located (risky country) and the US (as a risk-free reference country) to determine the developing country’s risk premium τ_i. The calculation of country-specific investment risks is based on data from the International Monetary Fund's International Financial Statistics (IFS) (IMF, 2000). IFS provides time series data for key economic indicators of most IMF members (over 200 countries), such as a country's exchange rates, international liquidity, money and banking accounts, interest rates, production indices, prices, international transactions, government accounts, and national accounts, as well as commodity and trade statistics. The data on long-term government bond yields that we use to measure the investment risk is given in monthly steps from 1981 to 2001. In order to aggregate the single country level data to the regions of our simulation model (see Table 6.1), the long-term government bond yields are weighted with the country’s share in direct investments of the associated region. The descriptive statistics of the country-specific risk premiums for the model regions with a mapping of IFS countries are given in Table 6.2. The expected risk premium $E\tau_i$ and the variance $V(\tau_i)$ are approximated by the sample mean and variance, respectively. Using this information, the expected return of investment projects in country *i*, its variance and standard deviation are given by: $EX_i = \left[(1-E\tau_i)\cdot p - c_i'\right] \big/ c_i'$, $V(X_i) = \left(p/c_i'\right)^2 \cdot V(\tau_i)$, and $\sigma_{X_i} = \left(p/c_i'\right)\cdot\sigma_{\tau_i}$, where σ_{τ_i} denotes the standard deviation of the yield spread.

For example, if the expected value of the yield spread of the country *i* (where the project is undertaken) amounts to τ_i = 0.1, the investing industrialized country obtains on average only 90 percent of the emission credits from projects carried out in this country due to the investment risk. The expected return for the marginal investment project that delivers one emission credit at price $c_i^{'}$ = 40 USD and saves abatement costs of *p* = 50 USD in the

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[58] Moody's long-term bond rating classifications range from Aaa (the best) to C (the worst). The default spreads for different countries associated with the bond ratings are e.g. 4.5 % for Brazil (B1), 0.95 % for China (A3), 7.5 % for Cuba (Caa1), 3% for India (Ba2), and 6.5 % for Indonesia (B3) (Damodaran, 1999).

industrialized country is EX_i = 0.19 with investment risk and Y_i = 0.25 without investment risk considerations. If the variance of the country-specific risk premium is assumed to be $V(\tau_i)$ = 0.01 (i.e. the standard deviation amounts to σ_{τ_i} = 0.10) the variance of the project return is $V(X_i)$ = 0.016, and the standard deviation is σ_{X_i} = 0.125.

Table 6.2 Descriptive statistics of bond yield spreads τ

Regions	IFS countries	Obs.	Mean	Median	StdDev	Skew	Kurtosis	Max	Min
AFR	Malawi, South Africa, Namibia, Zimbabwe	264	0.051	0.061	0.041	–0.507	2.092	0.135	–0.043
ASI	Thailand, Korea, Malaysia, Singapore, Sri Lanka	264	0.028	0.026	0.017	0.297	2.134	0.069	-0.005
CHN	China	144	0.042	0.034	0.028	0.207	1.937	0.110	–0.004
IND	India	86	0.061	0.061	0.014	–0.095	2.195	0.088	0.031
MPC	Mexico, Morocco	34	0.016	0.012	0.013	0.484	2.075	0.039	–0.005
MSA	Venezuela, Jamaica, Antilles, Honduras, Chile	264	0.062	0.048	0.067	1.536	6.946	0.407	–0.025

Source: Own calculation based on IMF (2000)

We implement the different attitudes towards risk as described in Section 6.2.2 through explicit constraints on the ratio of the price received for the emission credit over the marginal costs of the project generating the credit unit in country *i*, i.e. p/c_i'. For the different risk attitudes, an investment in emission reduction projects is profitable as long as:

$$\frac{p}{c_i'} \geq \frac{1}{1-E\tau_i} \qquad (\mu) \tag{6.10}$$

$$\frac{p}{c_i'} \geq \frac{1-E\tau_i-\sqrt{(1-E\tau_i)^2-2\cdot\alpha\cdot V(\tau_i)}}{\alpha\cdot V(\tau_i)} \qquad (\mu,\sigma) \tag{6.11}$$

$$\frac{p}{c_i'} \geq \frac{1}{1-E\tau_i-\beta\cdot\sigma_{\tau_i}} \qquad (VaR) \tag{6.12}$$

Figure 6.2 illustrates the effect of changes in the risk aversion parameters α under (μ,σ) preferences and β under VaR preferences on the price-cost-ratio of emission crediting between the industrialized world and the developing regions represented in our model. The ratio under μ and VaR preferences coincide for certain values of α and β, e.g. the ratio for developing region MSA is 1.1 for α = 11.9 and β = 0.44 (t = 0.67). In case $\alpha = \beta = 0$ the investment rule for μ and VAR preferences coincide with equation (6.10). The price-cost ratio increases faster in α and β for countries with relatively high variance of returns, such as AFR, MSA or CHN, while the ratio increases only slightly for countries with relatively low variance, i.e. ASI, MPC, IND. The basic message of Figure 6.2 is that risk aversion can substantially exacerbate the differences in attractiveness of investment projects across host countries. The increasing perceived costs associated with investment risks enlarge the departure of the equilibrium with investment risk from the equilibrium in the absence of investment risk and drive up the total aggregate compliance costs.

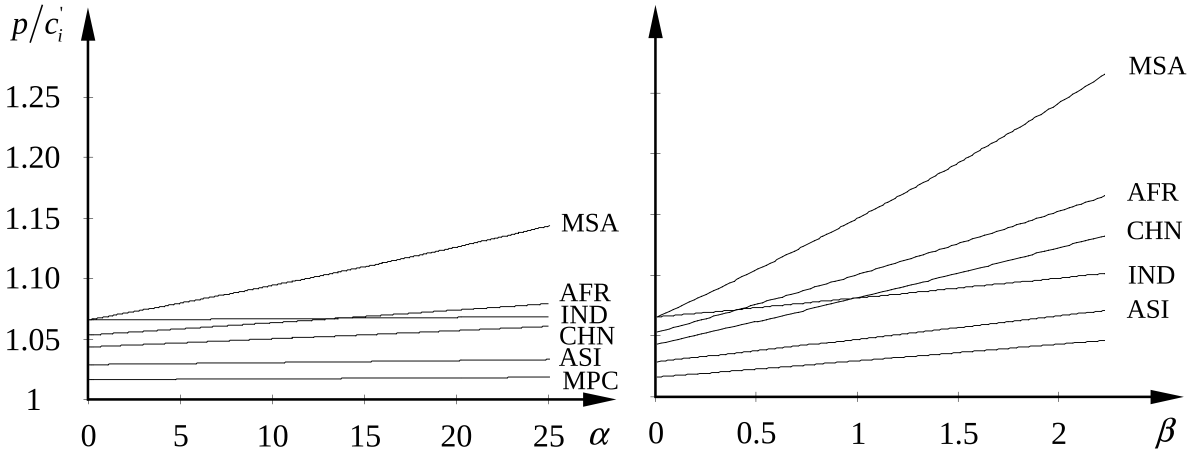

Figure 6.2 Price-cost-ratios for different risk aversion coefficients

6.4 Scenarios and Results

For our central case simulations, we assume a uniform 20 % cutback requirement of carbon emissions across industrialized countries vis-à-vis the business-as-usual emission level in 2010 (see Table 6.1) while developing countries remain uncommitted. This setting reflects two key ideas of international climate policy: Firstly, long-term stabilization of greenhouse gas concentrations in the atmosphere at levels recommended by the International Panel on Climate Change (IPCC, 2001) requires substantial emission cutbacks compared to the business-as-usual. Secondly, international climate policy has assigned the leading role in emissions abatement to the industrialized countries who have assumed historical responsibility for the greenhouse gas problem.[59]

To provide a meaningful basis of comparison, we first investigate a set of three scenarios that reflect different degrees in where-flexibility while abstracting from risk considerations:

NTR Industrialized countries apply carbon taxes that are high enough to meet their domestic emission abatement targets (equivalently they may establish a domestic tradable permit system).

CLUB Industrialized countries can trade emission rights with each other but are not allowed to purchase project-based emission credits from developing countries.

GLOBAL There are no restrictions to where-flexibility. Beyond trading emission rights among each other, industrialized countries can buy emission credits from developing countries through abatement projects. Investment risks are neglected.

A second set of scenarios extends the specification of the *GLOBAL* scenario by alternative risk attitudes of investors towards CDM projects in developing countries:[60]

μ Investors are risk-neutral and discount emission credits purchased through CDM projects with the mean risk value of the developing country where projects are undertaken.

(μ,σ) Investors adopt the mean-variance criterion. Covering the wide range of possible Arrow-Pratt coefficients, we choose a lower bound value ($\alpha = 10$) to characterize a risk-averse agent and an upper bound value ($\alpha = 25$) to characterize a highly risk-averse agent.

VaR Investors behave according to the Value at Risk (*VaR*) criterion. Without any distributional assumption imposed, we select two alternative values for β that

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[59] The Kyoto Protocol, which has originally been drafted along these lines, has meanwhile stripped down to a symbolic policy (see Chapter 4) and, thus, does not provide a useful reference scenario for our analysis.

[60] We assume that the risks of emission trading between industrialized countries can be neglected.

correspond to a confidence level of about either 0.75 (i.e. $\beta = 2$) or 0.95 (i.e. $\beta = 4$).[61]

Table 6.3 reports the simulation results for the first set of scenarios.[62] Without emission trading (scenario *NTR*), each industrialized country has to meet its reduction target exclusively by domestic action. The associated marginal abatement costs per ton of carbon range from 55 USD for FSU up to 195 USD for CAN. Given the same relative reduction target, differences in marginal costs across countries can be traced back to cross-country differences in energy and carbon intensities, initial energy prices[63] or the ease of carbon substitution through fuel switching or energy savings as embodied in the respective marginal abatement cost curves. Compliance costs for the *NTR* case correspond to inframarginal abatement costs by taking the integral of the marginal abatement cost curve.

Where-flexibility through emission trading across industrialized regions (scenario *CLUB*) reduces aggregate compliance costs by roughly 15 % providing a pareto-superior solution to the *NTR* scenario.[64] Countries whose marginal abatement costs under *NTR* are below equalized abatement costs under *CLUB* export carbon rights, thereby abating more emissions domestically than are required by their specific reduction target. Likewise, countries with higher domestic marginal abatement costs will become permit importers reducing their domestic abatement burden.

Unrestricted where-flexibility under *GLOBAL* through CDM projects between the developed world and developing countries will dramatically decrease the overall compliance costs by more than 70 % vis-à-vis the *NTR* cost level and about 65 % vis-à-vis the *CLUB* level. Direct revenues to developing countries under *GLOBAL* amount to roughly 8.4 bn USD. However, these are only the incremental abatement costs from abatement measures. Including additional FDI that would not have occurred otherwise, total investment flows to developing countries may be considerably larger (Zhang and Maruyama, 2001). It becomes clear that the CDM mechanism could provide substantial financial transfers to the developing world. In total revenue terms, CDM flows under *GLOBAL*, which are purely determined by

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[61] In Figure 6.2 we can see that these β-values under VaR correspond to higher α-values under (μ,σ) preferences, which implies higher risk aversion.

[62] Note that all of our quantitative results are readily replicable with the partial equilibrium model as captured by Equations (6.7) – (6.12) and the data provided by Table 6.1 and Table 6.2.

[63] For example, higher initial energy prices due to prevailing taxes require - ceteris paribus - higher carbon taxes in order to reach the same relative cutback in energy demand.

[64] In our partial equilibrium framework, we do not capture terms-of-trade effects that could make a single country worse off (see Böhringer and Rutherford, 2002).

marginal abatement costs and size of mitigation possibilities, will benefit CHN by far the most, since it disposes over large low-cost abatement options.

Global marginal abatement costs drop to 32 USD per ton of carbon, which is roughly a third of the CLUB level and falls substantially short of the lowest marginal abatement cost for purely domestic action of industrialized countries (*NTR*). As a consequence, all industrialized countries turn into net importers of emission rights. In total, the domestic abatement share of the industrialized world is less than 50 % with some countries fulfilling less than 30 % of their abatement duty through domestic mitigation projects: EUR, e.g., achieves only 29.7 % of its total abatement requirement of 208 MtC (i.e. 20% of 1040 MtC) domestically.

We now turn to the implications of risk in mitigation projects in developing countries, which are summarized for the second set of scenarios in Table 6.4. To accommodate a convenient comparison, the results for scenario *GLOBAL* that serve as the ‘no-risk’ reference case are reported again. In general, the accounting of risk should result in a reduction of total cost savings from CDM projects, since risk premia increase the costs for emission credits from the investor’s perspective. Consequently, domestic abatement action of industrialized countries should rise vis-à-vis the *GLOBAL* scenario. Country-specific risk premia imply non-uniform deductions from the (increased) uniform emission market price across CDM countries (see section A in Table 6.4). As has been pointed out in Section 6.3.2, low-risk countries may benefit from risk considerations at the expense of high-risk countries through both higher effective prices for carbon credits and more CDM projects compared to the case *GLOBAL*. The qualitative reasoning is confirmed by the quantitative results. With higher risk aversion, the market price for emission credits paid by industrialized countries increases and is accompanied by a decline in their cost savings from CDM projects and an increase in domestic action. As to developing countries, low-risk regions MPC and ASI fare better the more risk-averse investors become, while high-risk countries such as AFR and MSA do worse. The distribution of gains shows a similar distribution as FDI flows across developing countries (see Table 6.1).

Table 6.3 Economic impacts of carbon abatement

	NTR	*CLUB*	*GLOBAL*
A. Marginal abatement costs (in USD/tC)			
AUN	74.1	98.2	32.2
CAN	194.6	98.2	32.2
EIT	56.2	98.2	32.2
EUR	169.9	98.2	32.2
FSU	54.5	98.2	32.2
JPN	195.3	98.2	32.2
USA	89.5	98.2	32.2
All others	0	0	32.2
B. Cost of compliance (in million USD)			
AUN	789	720	560
CAN	2.699	2.096	895
EIT	984	540	822
EUR	14.922	12.516	5.549
FSU	2.605	1.305	2.221
JPN	5.513	4.261	1.809
USA	13.346	13.242	8.304
AFR	0	0	-675
ASI	0	0	-804
CHN	0	0	-5.372
IND	0	0	-613
MPC	0	0	-447
MSA	0	0	-475
Total	40.858	34.680	11.775
C. Domestic abatement share (in % of total abatement requirement) [a]			
AUN	100	121.6	56.1
CAN	100	60.9	27.1
EIT	100	149.4	66.9
EUR	100	67.0	29.7
FSU	100	148.7	70.1
JPN	100	59.8	26.0
USA	100	106.7	48.8
Total [b]	100	100	45.6

[a] Values below 100 % indicate permit imports, values above 100 % indicate permit exports.
[b] With respect to total industrialized emissions in 2010.

However, our quantitative results suggest that the risk-induced changes are relatively small. If investors are risk-neutral, i.e. for the scenario μ, the changes are close to negligible (e.g. with respect to country-specific compliance costs changes as compared to *GLOBAL* are only as high as 3 % with total compliance costs increased by 2.4 %). When investors decide according to the mean-variance criterion, the effects compared to *GLOBAL* are still very small. Even for $\alpha = 25$, the largest deviation from *GLOBAL* in country-specific compliance costs is about 4 % (regions MPC and MSA). The total increase in compliance costs amounts to 3.2 %.

The implications of risk become more relevant for the *VaR* scenario. When investors go for high safety of returns, compliance costs vary between 3 % (AFR, CHN) and 11 % (MPC, MSA). Total cost of compliance will increase to 10 % above the level of the *GLOBAL* scenario. As indicated by the larger differences in marginal abatement costs, we see a substantial shift in comparative advantage from high-risk countries AFR and MSA to low-risk countries MPC and ASI. The latter benefit in particular from higher country-specific project volumes, although the total amount of emission credits across all developing countries has distinctly declined. Towards higher overall risk perception in project-based emission crediting with developing countries, the domestic abatement share of industrialized countries increases from 45.6 % to 48.7 % (*VaR*, $\beta = 4$).

Table 6.4 Implications of investment risks

	GLOBAL	μ	(μ,σ)		*VaR*	
		$\alpha = \beta = 0$	$\alpha = 10$	$\alpha = 25$	$\beta = 2$	$\beta = 4$
A. Marginal abatement costs (in USD/tC)						
AUN	32.2	33.0	33.1	33.2	34.1	35.3
CAN	32.2	33.0	33.1	33.2	34.1	35.3
EIT	32.2	33.0	33.1	33.2	34.1	35.3
EUR	32.2	33.0	33.1	33.2	34.1	35.3
FSU	32.2	33.0	33.1	33.2	34.1	35.3
JPN	32.2	33.0	33.1	33.2	34.1	35.3
USA	32.2	33.0	33.1	33.2	34.1	35.3
AFR	32.2	31.3	31.1	30.8	29.6	27.7
ASI	32.2	32.1	32.1	32.2	32.0	31.9
CHN	32.2	31.6	31.5	31.5	30.8	29.9
IND	32.2	31.0	31.0	31.1	31.1	31.2
MPC	32.2	32.4	32.5	32.6	32.7	33.0
MSA	32.2	31.0	30.2	29.1	27.5	23.7

Table 6.4 continued

	GLOBAL	μ	(μ,σ)		*VaR*	
		$\alpha = \beta = 0$	$\alpha = 10$	$\alpha = 25$	$\beta = 2$	$\beta = 4$
B. Cost of compliance (in million USD)						
AUN	560	569	570	571	581	594
CAN	895	915	917	920	941	970
EIT	822	833	834	836	848	863
EUR	5.549	5.665	5.679	5.700	5.828	6.002
FSU	2.221	2.248	2.251	2.256	2.286	2.324
JPN	1.809	1.848	1.852	1.859	1.902	1.961
USA	8.304	8.451	8.468	8.494	8.653	8.867
AFR	-675	-676	-674	-672	-668	-656
ASI	-804	-821	-824	-829	-847	-876
CHN	-5.372	-5.427	-5.436	-5.451	-5.497	-5.565
IND	-613	-608	-611	-615	-631	-656
MPC	-447	-462	-464	-467	-480	-500
MSA	-475	-474	-467	-457	-451	-423
Total	11.775	12.061	12.095	12.147	12.466	12.904
C. Domestic abatement share (in % of total abatement requirement) [a]						
AUN	56.1	57.1	57.2	57.4	58.4	59.9
CAN	27.1	27.6	27.7	27.8	28.3	29.0
EIT	66.9	68.1	68.3	68.5	69.8	71.6
EUR	29.7	30.2	30.3	30.4	30.9	31.8
FSU	70.1	71.3	71.4	71.6	72.9	74.6
JPN	26.0	26.5	26.5	26.6	27.2	27.9
USA	48.8	49.7	49.8	49.9	50.9	52.1
Total [b]	45.6	46.4	46.5	46.7	47.5	48.7

[a] Values below 100 % indicate permit imports, values above 100 % indicate permit exports.

[b] With respect to total industrialized emissions in 2010.

6.5 Sensitivity Analysis

We have performed a 'piecemeal' sensitivity analysis with respect to the abatement target for industrialized countries, thereby setting the uniform carbon reduction requirements either at 10 % or 30 %. When emission targets for the industrialized world become more (less) stringent, marginal abatement costs increase (decrease) and the total domestic abatement share decreases (increases). Where-flexibility provides higher (lower) overall cost savings, while compliance costs for industrialized countries as well as benefits from CDM for developing countries rise (diminish) towards higher (lower) targets. Our central insight on the relatively small impacts of risk consideration under risk neutrality remains robust: Unless investors are very risk-averse, changes in the magnitude of compliance costs as well as the pattern of abatement are rather negligible.

Another issue addressed by our sensitivity analysis refers to the estimation of investment risks in Section 6.3.3. To illustrate the sensitivity of results to risk estimates, we have run two additional sub-scenarios for *VaR* ($\beta = 4$) with a 20 % reduction target where the mean value is augmented by either a single standard deviation or double that amount. Table 6.5 summarizes the results. We see that shifts in the assumed default spreads cause substantial effects. Higher spreads imply substantially higher international prices for emission credits, and the differences in risk premia across developing countries become much more pronounced for risk averse investors. The implied shifts in comparative advantage for undertaking CDM projects now become dramatic for the high-risk region MSA. Only very cheap CDM projects in MSA remain competitive after risk adjustment, thereby driving down its trading volume and the associated benefits from CDM close to zero. Although the global trade in emission credits shrinks, i.e. industrialized countries undertake much more abatement domestically, low-risk countries such as MPC gain both in terms of increased credit volume as well as higher prices, since they become relatively safer (more attractive) for investors from the developed world.

Table 6.5 Impacts of higher risk premia

	VaR ($\beta = 4$)		
	$E\tau_i$	$E\tau_i + \sigma_{\tau_i}$	$E\tau_i + 2\cdot\sigma_{\tau_i}$
Marginal abatement costs (in USD/tC)			
AUN	35.3	38.9	43.7
CAN	35.3	38.9	43.7
EIT	35.3	38.9	43.7
EUR	35.3	38.9	43.7
FSU	35.3	38.9	43.7
JPN	35.3	38.9	43.7
USA	35.3	38.9	43.7
AFR	27.7	22.5	16.4
ASI	31.9	31.8	31.9
CHN	29.9	27.5	24.7
IND	31.2	31.7	32.6
MPC	33.0	33.8	35.2
MSA	23.7	13.2	0.2
Cost of compliance (in million USD)			
AUN	594	629	671
CAN	970	1.052	1.159
EIT	863	901	941
EUR	6.002	6.500	7.144
FSU	2.324	2.420	2.517
JPN	1.961	2.128	2.346
USA	8.867	9.462	10.189
AFR	-656	-610	-528
ASI	-876	-961	-1.084
CHN	-5.565	-5.733	-5.934
IND	-656	-731	-841
MPC	-500	-562	-651
MSA	-423	-310	-21
Total	12.904	14.185	15.909

Table 6.5 continued

	VaR ($\beta = 4$)		
	$E\tau_i$	$E\tau_i + \sigma_{\tau_i}$	$E\tau_i + 2\cdot\sigma_{\tau_i}$
Domestic abatement share (in % of total abatement requirement) [a]			
AUN	59.9	64.0	69.4
CAN	29.0	31.1	33.9
EIT	71.6	76.7	83.4
EUR	31.8	34.1	37.1
FSU	74.6	79.6	86.1
JPN	27.9	30.1	32.7
USA	52.1	55.8	60.5
Total [b]	48.7	52.1	56.6

[a] Values below 100 % indicate permit imports, values above 100 % indicate permit exports.
[b] With respect to total industrialized emissions in 2010.

6.6 Conclusions

We have investigated how risk considerations affect the economic implications of emission crediting. Our quantitative results show that the incorporation of country-specific investment risks induces rather small changes to the magnitude and distribution of benefits from project-based emission trading vis-à-vis a situation where investment risks are neglected.

If investors go for high safety of returns, however, there is a noticeable decline in the overall volume of emission crediting and the associated total economic benefits. Differences in risk across developing countries then become more pronounced with converse implications for high-risk and low-risk developing countries. While low-risk developing countries attract higher project volumes and benefit from higher effective prices per emission credit compared to a reference scenario without risk, the opposite applies to high-risk countries. The - politically undesired – shift in comparative advantage of emission abatement against high-risk, typically least-developed, countries may become dramatic if risk-averse investors perceive large differences in project-based risks across countries. In this case, only very cheap mitigation projects in high-risk countries will be realized, driving down the respective country’s benefits from emission crediting to the advantage of low-risk developing countries.

This simulated pattern of regional imbalance is confirmed by the empirical evidence for activities implemented jointly (AIJ) that have been undertaken so far under the pilot phase of the Kyoto Protocol: Of the 152 AIJ projects in 2001, 85 have been concentrated in Latin America and Caribbean, 39 in Economies in Transition, 19 in the Asia and Pacific region, and only 9 in Africa (UNFCCC, 2001b).

Our simulation results indicate the importance of risk reduction measures in countries with high project risks. Such measures may include contractual agreements, financial project design, and insurance and guarantees by private and public institutions (Zhang and Maruyama, 2001; Dailamy and Leipziger, 1999). In addition, public funds, such as official development assistance and Global Environment Facility (GEF) funds, may be used to mitigate country risks associated with climate-friendly project investment and to counteract the risk-ridden shifts in mitigation projects across developing countries.

In our analysis, we have not investigated to what extent the asymmetric distribution of risks may affect global efficiency of ‘where’-flexibility for alternative initial distributions of abatement duties. As with transaction costs, permit market equilibrium and aggregate compliance costs will not be independent from the initial permit allocation (Montero, 1997; Stavins, 1995). This aspect is of potential importance with respect to future (Post-Kyoto) GHG abatement policies[65], which may include stringent emission reduction targets for the industrialized world as well as the developing world.

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[65] Expert judgements on likely climate policies beyond Kyoto are evaluated in Böhringer and Löschel (2003a).

7 Cost Prices and the True Cost of Labor [*]

7.1 Introduction

Computable general equilibrium (CGE) analyses have played a key role in the evaluation of green tax reforms, the reorientation of the tax system to concentrate taxes more on ‘bads’ like pollution and less on ‘goods’ like labor input or capital formation over the last ten years. The ongoing concern about the magnitude of distortionary taxation suggests the possibility of using environmental taxes to replace existing factor and commodity taxes. A conjecture called the ‘double dividend hypothesis’ points out that environmental taxes have two benefits: they discourage environmental degradation and they raise revenue that could offset other distortionary taxes.[66] The question in the double dividend debate therefore is whether the internalization of environmental externalities can be beneficial for other policy areas as well since the revenues from pollution taxes could be used to cut other distortionary taxes. The non-environmental dividend can be defined in various ways. Given the important unemployment problem in the EU, priority has been given to the analysis of distortions in the labor market that might explain persisting unemployment.[67] The revenue from the pollution taxes are recycled to cut labor taxes. On the one side, the narrow base of an energy tax constitutes an inherent efficiency handicap. On the other side, the impact of the tax reform on pre-existing inefficiencies in taxing labor could offset this handicap and a double dividend arises. Therefore, in principle a double dividend can arise only if (i) the pre-existing tax

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[*] This chapter is based on the paper ‘Recycling of Eco-Taxes, Labor Market Effects and the True Cost of Labor- A CGE Analysis’, with K. Conrad, *ZEW Discussion Paper 02-31*, Mannheim, 2002.

[66] For a state of the art review on the double dividend issue, see Goulder (1997) and Bovenberg and Goulder (2001).

[67] For theoretical papers on the double dividend issue, see Goulder (1995), Bovenberg and Goulder (1996). See Jorgenson and Wilcoxen (1992), Proost and van Regemorter (1995) and Welsch (1996b) for empirical papers.

system is significantly inefficient on non-environmental grounds and (ii) the revenue-neutral reform significantly reduces this prior inefficiency. The double dividend actually arises only if the second condition operates with sufficient force. However, it could also arise if the burden of the environmental tax falls mainly on the undertaxed factor (e.g. immobile capital) and relieves the burden of the overtaxed factor labor.[68] Since no existing tax systems are likely in a second-best optimum, the scope for a double dividend is always present.

Although CGE modeling has provided a number of important insights about the interplay between environmental tax policy and the pre-existing tax system, much remains to be done to improve our understanding of market-based environmental policy. One reason is that some CGE modelers affirm the double dividend hypothesis while others could not find a double dividend outcome. The specification of the labor market, for instance, could be crucial to the discussion on the effect of environmental policy on employment. A labor market policy of recycling tax revenues from an environmental tax to lower employers' non-wage labor cost depends on how the labor market is modeled. The objective of our analysis is not to show that non-competitive labor markets could provide a potential channel for a double dividend outcome. In the presence of wage setting institutions and involuntary unemployment a variety of approaches are discussed in the literature to analyze the impacts of an ecological tax reform. Typically, labor markets imperfections are introduced by an upward sloping wage setting curve which replaces the labor supply curve used in the competitive model. The equilibrium wage and employment level are now determined by the intersection of the wage setting and the labor demand curve. The theory of equilibrium unemployment offers three microeconomic models, which all capture specific institutional factors of actually existing labor markets – namely trade union models, efficiency wage models, and mismatch models. Each model is appropriate to describe a specific part of the multi-facetted phenomenon of involuntary unemployment. Unlike the recent double dividend literature, we will not emphasize the empirical relevance of a certain labor market model, but our aim is instead to attack the way, the costs of labor are conceived in all neoclassical models.

The objective of this chapter therefore is to advocate an approach where the cost of labor is not just wage per day, but the cost of the working place per day, including the wage. Such a view will have an impact on substitution possibilities and hence will affect the outcome of a double dividend policy. We will use an approach proposed by Conrad (1983)

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[68] See Bovenberg and Goulder (2001) on this point.

which combines the approaches to neoclassical substitutability and fixed factor proportions. This cost-price approach uses Leontief partially fixed factor proportions to identify both a disposable or variable part and a bound or fixed portion of each input. The true cost, or cost price, of any input consists of its own price plus the costs associated with the portion of that input bound to other inputs. As an example, the cost of an additional worker includes not just salary, but also the costs of inputs tied to the worker (e.g. office equipment, electricity, material, etc.). Within the cost-price framework, the demand for an input can be separated into a committed component linked to the use of other inputs, and a disposable component which is free for substitution. At one extreme, when the disposable quantities of all inputs equal zero, no factor substitution is possible and the cost-price approach reduces to the Leontief fixed-proportion case. At the other extreme, when the committed quantities of all inputs are zero, the neoclassical model is relevant and the cost-price of any input equates the market price. We will econometrically estimate cost share equations in cost-prices and then will use cost prices instead of market prices to investigate the double dividend hypothesis.

The Chapter is organized as follows. In Section 7.2, we present the cost-price approach and in Section 7.3 the parameter estimates for a restricted version of the manufacturing industry. In Section 7.4 we briefly outline our CGE model. In Section 7.5 we present our simulation results based on a CO_2 tax and the recycling of its revenues to reduce the non-wage labor cost. One simulation will be based on market prices and the other one on cost prices. Our objective is to compare the results in the light of the conjecture of a double dividend. The conclusion from our result is summarized in Section 7.6.

7.2 Conditioned Input Demand and Cost Share Equations in Cost-Prices

In contrast to Leontief production functions, we assume that only fractions of the input quantities are related to each other in fixed factor proportions and that therefore, in contrast to the neoclassical theory, only fractions of the input quantities are disposable for substitutions. With capital, labor and energy as inputs, we regard a truck, a truck driver and the minimal possible fuel consumption as bound inputs. In general, however, not the total quantity of an input is bound by other inputs with fixed proportions, but a fraction is unbound and disposable for substitution. It is this fraction which is relevant for a reallocation of inputs if relative factor prices change. If the energy price increases, the maintenance of the machinery will be improved (an additional worker), and truck drivers will drive slower (working overtime or less mileage per day). However, this substitution effect can primarily be observed with respect to the unbound component of an input; bound factors like machinery, the stock of trucks, or truck drivers are not objects of a substitution decision; they will be replaced either simultaneously or not at all as one more unit is linked to high costs due to bound inputs (an additional truck requires an additional truck driver). In case of a higher energy price, therefore, the disposable energy input will be the one that will be reduced. The fact that other inputs are bound to energy should be indicated by a cost-price or user cost in which the price of energy enters with an appropriate weight. In order to take into account this aspect, we separate the quantity of an input into a bound part and into an unbound one:[69]

$$v_i = \overline{v}_i + \tilde{v}_i , \qquad i = 1,...,n \tag{7.1}$$

where $\overline{v}_i$ is the number of units of factor *i* bound by the usage of the remaining $n-1$ inputs, and $\tilde{v}_i$ is the disposable quantity of factor *i*. The bound quantity of an input, $\overline{v}_i$, depends with fixed factor proportions upon the disposable quantities of the other inputs. Here, $\overline{v}_i$ is a simple sum, defined as

$$\overline{v}_i = \sum_{j \neq i} \alpha_{ij} \, \tilde{v}_j , \qquad \alpha_{ij} \geq 0 , \qquad i = 1,...,n \tag{7.2}$$

where α_{ij} is the quantity of v_i bound to one disposable unit of v_j. Substituting (7.2) into (7.1) yields

$$v_i = \sum_{j=1}^{n} \alpha_{ij} \, \tilde{v}_j , \qquad \text{where } \alpha_{ii} = 1 \tag{7.3}$$

by definition. If the disposable part of input *j* is increased by one unit, this increases the total quantity of input *j* by just this unit and all other inputs *i* (*i* = 1,..., *n*, $i \neq j$) by the quantities α_{ij}.

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[69] For more details see Conrad (1983).

These α_{ij} coefficients constitute a matrix $A=\left(\alpha_{ij}\right)$ which describes the degree of affiliation for any data set. If α_{ij} = 0 $(i \neq j)$ for all *i* and *j*, the neoclassical model is relevant and the cost-price of any input is its own price. If $\tilde{v}_i$ = 0 (or v_i = $\overline{v}_i$) for all *i*, no factor substitution is possible and the cost price approach reduces to the Leontief fixed proportion production function.

We next replace the quantities v_i in the cost minimizing approach by the partitioning given in Equation (7.3). Instead of

$$\min\left\{\sum_i P_i\, v_i \middle| x=H\left(v_i,...,v_n\right)\right\} \tag{7.4}$$

where *x* is the given output quantity, we write

$$\min\left\{\sum_j \tilde{P}_j\, \tilde{v}_j \middle| x=F\left(\tilde{v}_1,...,\tilde{v}_n\right)\right\} \tag{7.5}$$

where

$$\tilde{P}_j := \sum_i \alpha_{ij}\, P_i \qquad \text{and} \qquad \alpha_{jj}=1\,, \qquad j=1,...,n \tag{7.6}$$

is the cost-price of input *j*. It consists of its own price $\left(P_j\right)$ plus the additional costs associated with factors bound to v_j. By substituting the cost-minimizing factor demand functions $\tilde{v}_j = f_j\left(x;\, \tilde{P}_1,...,\tilde{P}_n\right)$ into Equation (7.3) we obtain the cost-minimizing input quantities in terms of cost prices $\tilde{P}_1,...\tilde{P}_n$. The dual cost function with respect to the cost prices is then:

$$C\left(x;\, \tilde{P}_1,...,\tilde{P}_n\right)=\sum_j \tilde{P}_j \cdot f_j\left(x;\, \tilde{P}_1,...,\tilde{P}_n\right). \tag{7.7}$$

The analogue to Shephard’s lemma (envelope theorem) holds:

$$\frac{\partial C\left(x;\,\tilde{P}\right)}{\partial \tilde{P}_i} = \tilde{v}_i \tag{7.8}$$

$$\frac{\partial C\left(x;\,\tilde{P}\right)}{\partial P_i} = \sum_j \left(\frac{\partial C}{\partial \tilde{P}_j}\right)\left(\frac{\partial \tilde{P}_j}{\partial P_i}\right) = \sum_j \alpha_{ij} \cdot \tilde{v}_j = v_i\,. \tag{7.9}$$

Equations (7.8) and (7.9) provide the disposable amounts of each input as well as the cost minimizing quantities of total inputs. From Equation (7.8), we can determine the cost shares $\left(w_i\right)$ of each factor as follows:

$$w_i = \frac{P_i \cdot v_i}{C} = P_i \left(\frac{\partial \ln C\left(x;\,\tilde{P}\right)}{\partial P_i}\right). \tag{7.10}$$

These shares equations can then be used to empirically estimate the parameters of the cost prices.[70] In the next section, we will estimate econometrically the cost-price model.

7.3 Empirical Results for a Cobb-Douglas Cost Function

As a specification of the cost function we will choose the simplest case, namely a cost function of the Cobb-Douglas type (henceforth CD). However, an approach with cost prices and committed inputs does not result in simple measures of the degree of substitutability as in the conventional CD case where the elasticity of substitution is unity and all inputs are price substitutes. As shown in Conrad (1983), even under the CD-assumption, variable elasticities of substitution and complementary relations are possible. Under our assumption of constant returns to scale and disembodied factor augmenting technical change, $b_j \cdot t$, the CD-cost function is:

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[70] Technical change can be introduced into the cost prices as described below (see Olson and Shieh, 1989), but we have omitted this aspect in our static CGE analysis.

$$\ln C\left(x;\, \tilde{P}\right) = \ln x + \alpha_0 + \sum_j \left(\gamma_j + b_j \cdot t\right) \ln \tilde{P}_j$$

where $\sum_j \gamma_j = 1$ and $\sum_j b_j = 0$. Because of Equation (7.10),

$$w_i = P_i \left\{ \sum_j \left[\frac{\left(\gamma_j + b_j \cdot t\right)}{\tilde{P}_j} \right] \alpha_{ij} \right\} \tag{7.11}$$

where $\tilde{P}_j = P_j + \sum_{k \neq j} \alpha_{kj}\, P_k$.

We have nested the inputs of a sector, based on an input-output table with 49 sectors, such that on the first stage the inputs for the CD-production function are capital *K*, labor *L*, electricity *E*, material *M*, and fossil fuel *F*. As data for disaggregated energy inputs are available only for a short period of time (1978-90), we are constrained to a pooled time-series cross-section approach.[71] A total of 49 sectors for which data are available in the German national account statistics are pooled into four sector aggregates:

- the energy supply sectors aggregate
- the energy-intensive manufacturing sectors aggregate
- the non-energy-intensive manufacturing sectors aggregate
- the service sectors aggregate.

The five-equation system, consisting of the five cost-share equations for *K*, *L*, *E*, *M*, *F*, is estimated for each of the four sector aggregates, employing the panel data set in yearly prices and cost shares. It is assumed that the cost prices are identical in each sector aggregate, i.e. sectoral dummy variables are added only to the coefficients γ_i in Equation (7.11).

Due to the high degree of non-linearity inherent in the share equations, we have simplified our approach by concentrating on the cost-price of labor. Hence, the composition in Equation (7.3) is reduced to

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[71] For more details see Koschel (2001) and Falk and Koebel (1999).

$$K_i = \alpha_{KL} \cdot \tilde{L}_i + \tilde{K}_i ,\; L_i = \tilde{L}_i ,\; E_i = \alpha_{EL} \cdot \tilde{L}_i + \tilde{E}_i ,\; M_i = \alpha_{ML} \cdot \tilde{L}_i + \tilde{M}_i ,\; F_i = \alpha_{FL} \cdot \tilde{L}_i + \tilde{F}_i \quad (7.12)$$

where *i* = 1,2,3,4 for the four sector aggregates. The cost-prices for *K*, *E*, *F*, *M* are therefore market prices, i.e. $\widetilde{PK}_i = PK_i$, $\widetilde{PE}_i = PE_i$, $\widetilde{PM}_i = PM_i$ and $\widetilde{PF}_i = PF_i$. The cost-price of labor is:

$$\widetilde{PL}_i = PL_i + \alpha_{KL} \cdot PK_i + \alpha_{EL} \cdot PE + \alpha_{FL} \cdot PF_i + \alpha_{ML} \cdot PM_i \quad (7.13)$$

As mentioned before, α_{iL}, *i* = *K*, *E*, *M*, *F* are the same for each sector aggregate and so are the technical progress parameters b_i, *i* = *K*, *L*, *E*, *M*, *F*. The system of cost share equations we have to estimate is

$$w_{L,i} = \frac{PL_i \cdot L_i}{C_i} = \frac{\left(\gamma_{L_i} + b_L \cdot t\right) \cdot PL_i}{\widetilde{PL}_i} \quad (7.14)$$

$$w_{K,i} = \frac{PK_i \cdot K_i}{C_i} = \gamma_{K_i} + b_K \cdot t + \frac{\alpha_{KL} \cdot \left(\gamma_{L_i} + b_L \cdot t\right) \cdot PK_i}{\widetilde{PL}_i} \quad (7.15)$$

$$w_{E,i} = \frac{PE_i \cdot E_i}{C_i} = \gamma_{E_i} + b_E \cdot t + \frac{\alpha_{EL} \cdot \left(\gamma_{L_i} + b_L \cdot t\right) PE_i}{\widetilde{PL}_i} \quad (7.16)$$

$$w_{M,i} = \frac{PM_i \cdot M_i}{C_i} = \gamma_{M_i} + b_{M_i} \cdot t + \frac{\alpha_{ML} \left(\gamma_{L_i} + b_L \cdot t\right) PM_i}{\widetilde{PL}_i} \quad (7.17)$$

$$w_{F,i} = \frac{PF_i \cdot F_i}{C_i} = \gamma_{F_i} + b_F \cdot t + \frac{\alpha_{FL} \left(\gamma_{L_i} + b_L \cdot t\right) PF_i}{\widetilde{PL}_i} \quad (7.18)$$

with $\widetilde{PL}_i$ as given in Equation (7.13). In addition to using nonlinear techniques, the cost price model must be estimated with non-negativity constraints imposed on the parameters α_{iL}, i = K, E, M, F. Table 7.1 presents the estimated parameters.

Table 7.1 Maximum likelihood estimates for the parameters of the cost-prices and of technical change (asymptotic t-ratios in parentheses)

γ_K	0.092	(17.173)	b_K	$8.5\cdot10^{-4}$	(0,935)	α_{KL}^{**}	0.002	(0,431)
γ_L	0.458	(11.340)	b_L	-0.005	(-1,824)	α_{EL}	0.055	(2,611)
γ_E	$4\cdot10^{-8}$	$(6\cdot10^{-6})$	b_E	$4.2\cdot10^{-4}$	(1,889)	α_{FL}	0.072	(2,993)
γ_F	0.048	(3.508)	b_F	-0.002	(-1,143)	α_{ML}	0.422	(3,128)
γ_M^{*}	0.402	–	b_M^{*}	0.006	–			

* As the error terms add to zero, they are stochastically dependent and we have omitted equation (7.17) for estimation.

** Note that α_{KL} is not significant.

The bias of technical change is capital, electricity and material using (b_K >0, b_E >0, b_M >0), and labor and fossil fuel saving (b_L <0, b_F <0). The cost price of labor (Equation 7.13) is

$$\widetilde{PL} = PL + 0.002 \cdot PK + 0.055 \cdot PE + 0.422 \cdot PM + 0.072 \cdot PF \ . \qquad (7.19)$$

Using the α_{iL} parameter estimates in Table 7.1, we conclude from Equation (7.12) that an additional unit of labor needs 0.002 units of capital, 0.055 units of electricity, 0.422 units of material and 0.072 units of fossil fuel. In other words, reducing labor input by one unit will release 0.002 units of capital, 0.055 units of electricity, 0.422 units of material and 0.072 units of fossil fuel for possibilities of substitution as the disposable components $\tilde{K}$, $\tilde{E}$, $\tilde{M}$, $\tilde{F}$ increase with the reduction of $L \left(= \tilde{L}\right)$. In the next section we will use committed inputs, disposable inputs, and the corresponding cost-price of labor within the framework of a CGE model to investigate their impact on the outcome of the double dividend conjecture.

7.4 The Features of the CGE Model

This section presents the main characteristics of the comparative-static multi-sector CGE model of Chapter 2 for the German economy augmented with different costing concepts. The concrete specification of the model covers seven sectors and two factors. The energy goods identified in the model are coal (COL), natural gas (GAS), crude oil (CRU), refined oil products (OIL) and electricity (ELE). Non-energy production consists of an aggregate energy-intensive sector (EIS) and the rest of production (OTH). Primary factors include labor and capital, which are both assumed to be intersectorally mobile. Table 7.2 summarizes the sectors and primary factors incorporated in the model.

Table 7.2 Overview of sectors and factors

Sectors				Primary factors	
1	COL	Coal	– F	CAP	Capital – K
2	OIL	Refined oil products		LAB	Labor – L
3	GAS	Natural gas			
4	ELE	Electricity	– E		
5	CRU	Crude oil	– M		
6	EIS	Energy-intensive sectors			
7	OTH	Rest of industry			

Figure 7.1 illustrates the nested structure in production. At the top level, we have the KLEMF-structure with the CD specification in cost-prices. At the second level, a CES function describes the substitution possibilities between the material components. The primary energy composite is defined as a CES function of coal, oil and natural gas. Key substitution elasticities are given in the Appendix 7.A.

The government distributes transfers and provides a public good (including public investment) which is produced with commodities purchased at market prices. In order to capture the implications of an environmental tax reform on the efficiency of public fund raising, the model incorporates the main features of the German tax system: income taxes including social insurance contributions, capital taxes (corporate and trade taxes), value-added taxes, and other indirect taxes (e.g. mineral oil tax).

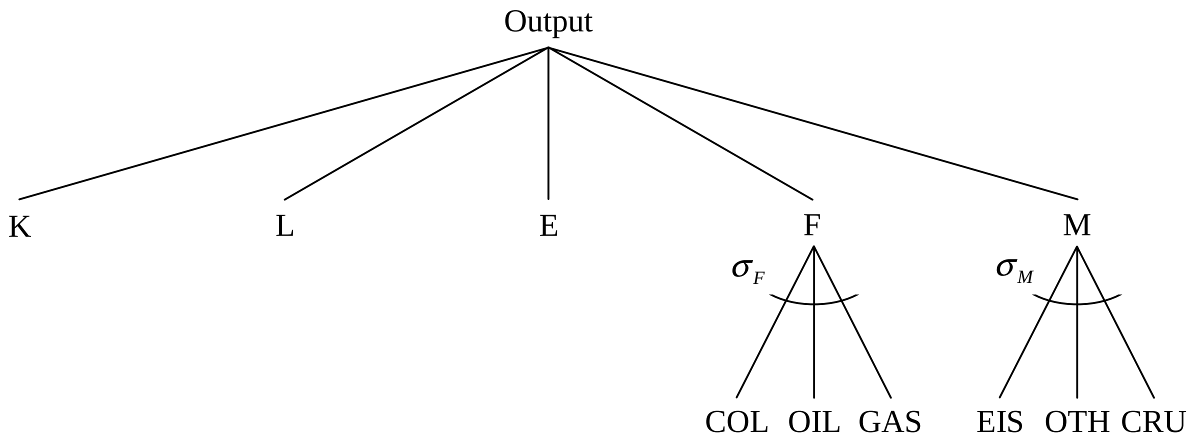

Figure 7.1 Nested structure of production

All commodities are traded internationally. We adopt the Armington assumption that goods produced in different regions are qualitatively distinct for all commodities. There is imperfect transformability (between exports and domestic sales of domestic output) and imperfect substitutability (between imports and domestically sold domestic output). 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 and international sales is characterized by a constant elasticity of transformation (CET) function. Intermediate and final demands are (nested CES) Armington composites of domestic and imported varieties. Germany is assumed to be a price-taker with respect to the rest of the world (ROW), which is not explicitly represented as a region in the model. Trade with ROW is incorporated via perfectly elastic ROW import-supply and export-demand functions. There is an imposed balance-of-payment constraint to ensure trade balance between Germany and the ROW. That is, the value of imports from ROW to Germany must equal the value of exports to ROW after including a constant benchmark trade surplus (deficit).

The analysis of the employment effects associated with an environmental tax reform requires the specification of unemployment. In our formulation, we assume that unemployment is caused by a rigid and too high consumer wage (see, for example, Bovenberg and van der Ploeg, 1996).

For each input structure of the industries, we choose the KLEMF-model at the top level. We employ in the cost share equations and in the cost price of labor the parameters, estimated from another source of input-output tables. Since the cost shares within the six industries differ from the cost shares calculated in the econometric part, we have to calibrate one parameter per cost share in order to adjust the estimated cost shares to the observed ones in the 7-industry base year table. Therefore, γ_{L_i} (i = 1,...,7) follows from Equation (7.14), given the cost shares of the 7-industry table. If γ_{L_i} is determined, γ_{K_i}, γ_{E_i}, γ_{F_i} and γ_{M_i} can be calculated from Equations (7.15) – (7.18).

Allen elasticities (σ_{ij}) for the Cobb-Douglas function in cost prices for each sector can be calculated.[72] They are related to the price elasticities of demand for factors of production (ε_{ij}) according to $\varepsilon_{ij} = \sigma_{ij} \cdot w_j$, i, j = K,L,E,F,M. Table 7.7 in the appendix presents Allen elasticities and price elasticities of demand in the CGE model with the parameter estimates of the cost-price model. Capital is a substitute for all inputs with an elasticity of substitution close to one. Electricity and fossil fuel have a complementary relationship to labor; material is a substitute for labor, for electricity and for fossil fuel; electricity and fossil fuel are complements in the non-energy intensive industries (OTH).

The disposable quantities of each factor of production can be derived from Equation (7.12). The disposable quantity of material, for instance, is

$$\widetilde{M}_i = M_i - a_{ML} \cdot L_i , \quad i = 1,2,...,7$$

From Table 7.3 we observe that in the non-energy-intensive industries 82 percent of electricity is bound to labor whereas in the energy intensive industries (EIS) only 16 percent are bound to labor; i.e. up to 84 percent are either bound to capital or disposable for substitution. For materials, 13% of this input in the sector OTH is bound to labor and 87 percent is free for substitution. In the industry EIS only 6 percent is linked to labor and 94 percent is substitutable. Similarly as for electricity, a high percentage of fossil fuel (96 percent) is linked to labor in the industry OTH and only 22 percent in the energy intensive industry EIS. In this industry, about 80 percent of fossil fuel is a candidate for substitution, whereas in other industries (OTH) only 4 percent is such a candidate.

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[72] See the Appendix 7.A.

Table 7.3 Disposable and bounded fraction of each factor of production in the CGE model

	Disposable		Bound (to labor)	
	OTH	EIS	OTH	EIS
K	0.999	0.999	0.001	0.001
L	1	1	0	0
E	0.185	0.841	0.815	0.159
M	0.868	0.937	0.132	0.063
F	0.040	0.784	0.960	0.216

Under constant returns to scale and price-taking behavior, the price of an industry *j*, P_j, is equal to its unit cost:

$$P_j = c_j\left(PK, \widetilde{PL}_j, PE, PM_j, PF_j\right).$$

Written in logarithmic terms, using our CD specification in cost-prices, we obtain

$$\begin{aligned}\ln P_j = &\left(\gamma_{K_j} + \beta_K \cdot t\right)\ln PK + \left(\gamma_{L_j} + \beta_L \cdot t\right)\ln \widetilde{PL}_j + \left(\gamma_{E_j} + \beta_E \cdot t\right)\ln PE \\ &+ \left(\gamma_{M_j} + \beta_M \cdot t\right)\ln PM_j\left(P_5, P_6, P_7\right) + \left(\gamma_{F_j} + \beta_F \cdot t\right)\ln PF_j\left(P_1, P_2, P_3\right).\end{aligned}$$

In addition, we have unit cost functions of the CES type for material, $PM_j = f_j\left(P_5, P_6, P_7\right)$, *j* = 1,2,...7, and for fossil fuel, $PF_j = f_j\left(P_1, P_2, P_3\right)$, j = 1,2,...7. In order to solve the price system $P_1, ..., P_7$, we have to add the labor-cost price equations (7.13), where $PL_j = PL$ for all *j*. If the price system has been solved, next price dependent input-output coefficients as derived input demand functions can be determined and the sectoral output levels can finally be calculated. A detailed description of the model is given in the Appendix 7.A. The main data source underlying the model is the GTAP version 4 database, which represents global production and trade data for 45 countries and regions, 50 commodities and 5 primary factors (McDougall et al., 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.

7.5 Empirical Results

In our simulation, we distinguish two types of scenarios. In each simulation, carbon taxes are levied in order to meet a 21 percent reduction of domestic carbon dioxide emissions as compared to 1990 emission levels. This is the reduction target the German government has committed itself to in the EU Burden Sharing Agreement adopted at the environmental Council meeting by Member States on June 1998. One type of simulation is based on the market price of labor and the second type on the cost price of labor. We impose revenue-neutrality in the sense that the level of public provision is fixed. Subject to this equal-yield constraint, we consider two ways to recycle the CO_2 tax revenue for each type of simulation. One way is to recycle it by a lump-sum transfer (LS) to the representative household. The other way is to adopt an environmental tax reform (ETR) in view of the adverse employment effects of carbon emission constraints. In such a case, the tax revenue is used to lower the non-wage labor costs (social insurance payment). Table 7.4 summarizes the implications of the two types of simulation studies under two ways of recycling the tax revenues. If firms decide on production and substitution on the base of the market price of labor and the tax revenue is recycled by a lump-sum transfer, then employment rate will be lower by 0.15 percent (see column 1 in Table 7.4). Welfare, expressed here as a change in GDP, will be lower by 0.55 percent. The CO_2 tax rate at the 21 percent CO_2 reduction level (marginal abatement cost) is 13.9 US$ per ton. Production in all industries declines, succeeding by a lower demand for labor. If the tax revenue is used to lower non-wage labor costs, we obtain an employment dividend because employment increases by 0.43 percent. Since GDP does not increase (–0.38 percent), we do not obtain a ‘strong double dividend’ where the level of emissions is reduced and employment and GDP are increased from the tax reform by itself. The positive substitution effect on labor from the ETR outweighs the negative output effect on labor. For the producer, the price of labor is lower by 0.72 percent compared to the policy of a lump-sum transfer (last rows in Table 7.4). The prices *PF* of fossil fuel have increased by the CO_2 tax, and this increase differs by industry according to the size and composition of this input.

The results under the user cost (cost-price) concept of labor can be explained best by comparing the change of the market price of labor with the change of the user cost of labor after the ETR. From the producer’s point of view, the price of labor declined by 0.72 percent after the ETR but only by about 0.59 percent under the user cost concept (see % change of $\widetilde{PL}$ in the corresponding industries). As the second half of Table 7.4 shows, the cost-price of labor differs by industry because the price aggregates *PM* and *PF* in Equation (7.19) differ by industry.[73] Since direct wage costs are only about two-thirds of the user cost of labor, the reduction in the cost of labor from the cut in social insurance payments is smaller under the cost-price concept. Hence, the substitution effect on labor is weaker and is outweighed by the negative output effect from higher energy prices (lower GDP). Therefore, we do not obtain a double dividend under the cost-price concept. The higher price $\widetilde{PL}$ from Equation (7.19) (about 1.55) is not the reason for this result, because this figure is taken into account when calibrating the parameters. The crucial impact comes from the aspect that a higher price of energy also raises the cost-price of labor because workers need energy in order to be productive. Therefore, employment declines more under the cost-price approach than under the market price approach (–0.55 versus –0.15 percent). When the tax revenue is recycled, the firm perceives a reduction of the cost-price by 0.59 percent on the average which is too small to induce a substitution process high enough to yield a double dividend. Although the decline in GDP is less under the cost-price approach than under the market price approach (–0.22 versus –0.38 percent), the incentive for substitution is weaker under the cost price approach and therefore employment declines (–0.06 versus 0.43 percent).

7.6 Conclusion

Policy makers are used to an economist’s advice that the outcome of a policy is ambiguous and depends on assumptions made. This fact makes our consulting work not very attractive. However, we think that our point that user costs of labor matter more than the normal wage costs is intuitively attractive when arguing about the double dividend hypothesis.

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[73] The cost-price approach has not been adopted for the industries coal, crude oil, and gas.

Table 7.4 Empirical results (LS – lump-sum transfer, ETR – environmental tax reform)

	Market price of labor		User cost of labor	
	LS	ETR	LS	ETR
Employment	–0.15	0.43	–0.55	–0.06
Consumption	–0.47	–0.14	–0.38	–0.02
Carbon tax*	13.92	14.24	14.54	14.92
GDP	–0.55	–0.38	–0.43	–0.22
Labor demand				
OTH	0.12	0.70	–0.24	0.24
EIS	–1.32	–0.72	–1.64	–1.13
COL	–25.79	–25.75	–25.71	–25.70
OIL	–4.95	–4.39	–5.17	–4.69
GAS	–10.42	–9.72	–10.89	–10.29
ELE	–0.11	0.51	–1.07	–0.47
Production				
OTH	–0.11	0.08	–0.02	0.21
EIS	–2.07	–1.86	–1.67	–1.40
COL	–25.76	–25.96	–25.73	–25.99
OIL	–5.19	–4.97	–5.28	–5.02
CRU	–2.55	–3.61	–4.08	–5.42
GAS	–10.38	–9.90	–10.91	–10.53
ELE	–3.53	–3.22	–2.38	–2.02
PL (producer cost)	1	0.9928	1	0.9927
PL (consumer wage)	1	1	1	1
PK	0.9992	0.9977	1.0005	0.9993
PE	1.0355	1.0310	1.0246	1.0199
PF – prices in the corresponding industries				
OTH	1.0632	1.0606	1.0650	1.0625
EIS	1.0949	1.0929	1.0982	1.0964
ELE	1.3708	1.3743	1.3869	1.3919
PM – prices in the corresponding industries				
OTH	1.0031	0.9997	1.0022	0.9986
EIS	1.0057	1.0023	1.0045	1.0009
OIL	1.0032	0.9999	1.0023	0.9988

Table 7.4 continued

Cost prices – $\widetilde{PL}$ in the corresponding industries				
OTH	1	0.9928	1.5582	1.5490
EIS			1.5616	1.5524
COL			1	0.9927
OIL			1.4251	1.4164
CRU			1	0.9927
GAS			1	0.9927
ELE			1.1016	1.0947
% change of $\widetilde{PL}$ in the corresponding industries				
OTH	–0.7240		–0.5936	
EIS			–0.5898	
COL			–0.7275	
OIL			–0.6147	
CRU			–0.7275	
GAS			–0.7275	
ELE			–0.6291	

* In US$. All other figures are percentage values or price indices.

Appendix 7.A Description of the Model and Parameterization

The appendix provides an algebraic summary of the comparative-static model. Table 7.5 explains the notations for variables and parameters. Table 7.6 gives key substitution elasticities. Table 7.7 presents Allen elasticities of substitution and price elasticities of demand for the Cobb-Douglas function in cost prices in the CGE model.

Zero profit conditions

$$\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}} \geq PK^{\gamma_{K_i}} \cdot \widetilde{PL}_i^{\gamma_{L_i}} \cdot PE^{\gamma_{E_i}} \cdot PM_i^{\gamma_{M_i}} \cdot PF_i^{\gamma_{F_i}} \quad \perp Y_i \qquad (7.A1)$$

$$\text{with} \quad \widetilde{PL}_i = PL + \alpha_{KL} \cdot PK + \alpha_{EL} \cdot PE + \alpha_{ML} \cdot PM_i + \alpha_{FL} \cdot PF_i \,,$$

$$PM_i = \left[\sum_{j=4}^{6} \mathrm{c}_{ij}^{\sigma_M} \cdot PA_j^{1-\sigma_M}\right]^{\frac{1}{1-\sigma_M}}, \; PF_i = \left[\sum_{j=1}^{3} \mathrm{d}_{ij}^{\sigma_F} \cdot PA_j^{1-\sigma_F}\right]^{\frac{1}{1-\sigma_F}}$$

$$PA_i \geq \left[\mathrm{e}_1^{\sigma_A} \cdot P_i^{1-\sigma_A} + \mathrm{e}_2^{\sigma_A} \cdot PFX^{1-\sigma_A}\right]^{\frac{1}{1-\sigma_A}} + \mathrm{a}_i^{CO} \cdot PCO \qquad \perp A_i \qquad (7.A2)$$

$$PC \geq \left[\mathrm{f}_1^{\sigma_C} \cdot \left(\prod_{i=1}^{4} PA_i^{\mathrm{g}_{1i}}\right)^{1-\sigma_C} + \mathrm{f}_2^{\sigma_C} \cdot \left(\prod_{j=5}^{7} PA_j^{\mathrm{g}_{2j}}\right)^{1-\sigma_C}\right]^{\frac{1}{1-\sigma_C}} \qquad \perp C \qquad (7.A3)$$

$$PZ \geq \left(\sum_{\mathrm{i}=1}^{3} \mathrm{h}_{1i}^{\sigma_G} \cdot PA_i^{1-\sigma_G}\right)^{\frac{1-\Sigma_{\mathrm{j}} \mathrm{h}_{2j}}{1-\sigma_G}} \cdot \prod_{j=4}^{7} PA_j^{\mathrm{h}_{2j}} \qquad \perp Z \qquad (7.A4)$$

Input and output coefficients

$$\mathrm{a}_i^K = w_{K,i} \cdot \frac{\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}}}{PK} \qquad (7.A5)$$

$$\mathrm{a}_i^L = \gamma_{L,i} \cdot \frac{\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}}}{\widetilde{PL}_i} \qquad (7.A6)$$

$$\mathrm{a}_{ji}^Y = w_{F,i} \cdot \frac{\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}}}{PF_i} \cdot \left(\frac{\mathrm{d}_{ij} \cdot PF_i}{PA_j}\right)^{\sigma_F} \qquad j = 1, 2, 3 \qquad (7.A7)$$

$$\mathrm{a}_{ji}^{Y} = w_{E,i} \cdot \frac{\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}}}{PE} \qquad j = 4$$

$$\mathrm{a}_{ji}^{Y} = w_{M,i} \cdot \frac{\left[\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right]^{\frac{1}{1+\varepsilon}}}{PM_i} \cdot \left(\frac{\mathrm{c}_{ij} \cdot PM_i}{PA_j}\right)^{\sigma_M} \qquad j = 5, 6, 7$$

$$\mathrm{a}_{j}^{C} = \mathrm{f}_1^{\sigma_C} \cdot PC^{\sigma_C} \cdot \mathrm{g}_{1j} \cdot \left(\prod_{i=1}^{4} PA_i^{\mathrm{g}_{1i}}\right)^{1-\sigma_C} \Big/ PA_j \qquad j = 1, 2, 3, 4 \quad (7.A8)$$

$$\mathrm{a}_{j}^{C} = \mathrm{f}_2^{\sigma_C} \cdot PC^{\sigma_C} \cdot \mathrm{g}_{2j} \cdot \left(\prod_{i=5}^{7} PA_i^{\mathrm{g}_{2i}}\right)^{1-\sigma_C} \Big/ PA_j \qquad j = 5, 6, 7$$

$$\mathrm{a}_{j}^{Z} = \left(1 - \sum_{\mathrm{i}=4}^{7} \mathrm{h}_{2i}\right) \cdot PZ \cdot \left(\frac{\mathrm{h}_{1j}}{PA_j}\right)^{\sigma_G} \Bigg/ \left(\sum_{\mathrm{i}=1}^{3} \mathrm{h}_{1i}^{\sigma_G} \cdot PA_i^{1-\sigma_G}\right) \qquad j = 1, 2, 3 \quad (7.A9)$$

$$\mathrm{a}_{j}^{Z} = \mathrm{h}_{2j} \cdot \frac{PZ}{PA_j} \qquad j = 4, 5, 6, 7$$

$$\mathrm{a}_{i}^{H} = \left(\frac{\mathrm{e}_1 \cdot PA_i}{P_i}\right)^{\sigma_A}, \ \mathrm{a}_{i}^{M} = \left(\frac{\mathrm{e}_1 \cdot PA_i}{PFX}\right)^{\sigma_A} \qquad (7.A10)$$

$$\mathrm{a}_{i}^{D} = \left[P_i \Big/ \left(\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right)^{\frac{1}{1+\varepsilon}}\right]^{\varepsilon}, \ \mathrm{a}_{i}^{X} = \left[PFX \Big/ \left(\mathrm{b}_1 \cdot P_i^{1+\varepsilon} + \mathrm{b}_2 \cdot PFX^{1+\varepsilon}\right)^{\frac{1}{1+\varepsilon}}\right]^{\varepsilon} \quad (7.A11)$$

Market clearance conditions

$$\overline{K} \geq \sum_i \mathrm{a}_i^K \cdot Y_i \qquad \perp PK \qquad (7.A12)$$

$$\mathrm{U} \equiv \overline{\mathrm{L}} - \sum_{\mathrm{i}} \mathrm{a}_i^L \cdot Y_i \qquad (7.A13)$$

$$\overline{CO} \geq \sum_i \mathrm{a}_i^{CO} \cdot A_i \qquad \perp PCO \qquad (7.A14)$$

$$\mathrm{a}_i^D \cdot Y_i \geq \mathrm{a}_i^H \cdot A_i \qquad \perp P_i \qquad (7.A15)$$

$$A_i \geq \sum_j \mathrm{a}_{ij}^A \cdot Y_j + \mathrm{a}_i^I \cdot \overline{I} + \mathrm{a}_i^C \cdot C + \mathrm{a}_i^Z \cdot Z \qquad \perp PA_i \qquad (7.A16)$$

$$\sum_i PFX \cdot \mathrm{a}_i^X \cdot Y_i \geq \sum_i PFX \cdot \mathrm{a}_i^M \cdot A_i + D \qquad \perp PFX \qquad (7.A17)$$

$$C \geq \frac{M_{RA}}{PC} \qquad \perp PC \qquad (7.A18)$$

$$Z \geq \frac{M_G}{PZ} \qquad \perp PZ \qquad (7.A19)$$

Income definitions

$$M_{RA} = \left(1 - t \cdot \tau_{ETR}\right) \cdot PL \cdot \sum_i \mathrm{a}_i^L \cdot Y_i + \left(1 - t\right) \cdot PK \cdot \overline{K}$$

$$- PI \cdot \overline{I} - PC \cdot D + \tau_{LS} \cdot TR \qquad (7.A20)$$

$$\text{with} \qquad PI = \left[\sum_{i=1}^{7} \mathrm{a}_i^I \cdot PA_i \right]$$

$$M_G = PCO \cdot \overline{CO} + t \cdot \tau_{ETR} \cdot PL \cdot \sum_i \mathrm{a}_i^L \cdot Y_i + t \cdot PK \cdot \overline{K} - \tau_{LS} \cdot TR \qquad (7.A21)$$

Auxiliary equation

$$\overline{Z} \geq Z \qquad \perp \tau_{LS}, \tau_{ETR} \qquad (7.A22)$$

Table 7.5 Sets, activity and price variables, endowments

Sets	
i, j	Sectors and goods (7 commodities)
Activity variables	
Y_i	Aggregate production
A_i	Armington aggregate
C	Aggregate household consumption
Z	Aggregate government consumption
U	Unemployment
Price variables	
P_i	Output price
PA_i	Price of Armington aggregate
PE	Price of electricity $(= PA_{ELE})$
PM_i	Price of material aggregate
PF_i	Price of fossil fuel aggregate
PI	Composite price for investment
PFX	ROW export and import price
PC	Composite price for aggregate household demand (utility price index)
PZ	Composite price for government demand
PK	Price of capital services
PL	(Rigid) wage rate
PCO	Price of carbon emission rights (carbon tax)
Income variables	
M_{RA}	Income of representative agent
M_G	Government income
Auxiliary variables	
τ_{LS}, τ_{ETR}	Endogenous equal yield tax adjustment
Endowments	
$\overline{K}$	Aggregate capital endowment
$\overline{L}$	Aggregate labor endowment
$\overline{CO}$	Endowment with carbon emission rights

Table 7.5 continued

Input and output coefficients (per unit demand and supply)	
a_i^K	Capital demand
a_i^L	Labor demand
a_{ji}^Y	Intermediate demand for Armington good
a_j^C	Private demand for Armington good
a_j^Z	Government demand for Armington good
a_j^I	Investment demand for Armington good
a_i^H	Demand for domestic production
a_i^M	Demand for imports
a_i^D	Supply to domestic market
a_i^X	Supply to export market
a_i^{CO}	Carbon coefficient
Other parameters	
$\overline{Z}$	Exogenously-specified (fixed) demand for public output
$\overline{I}$	(Fixed) aggregate investment level
D	Balance of payment surplus
TR	Lump sum transfers
t	Income tax
$\alpha_{KL}, \alpha_{EL}, \alpha_{ML}, \alpha_{FL}$	Cost price coefficients
$\gamma_{K_i}, \gamma_{L_i}, \gamma_{E_i}, \gamma_{M_i}, \gamma_{F_i}$	Calibrated cost price parameters
b, c, d, e, f, g, h	Technology coefficients

Table 7.6 Key substitution elasticities

Description		Value
Substitution elasticities in production		
σ_M	Material vs. material	0.5
σ_F	Fossil fuel vs. fossil fuel	0.3
Substitution elasticities in private demand		
σ_C	Energy goods vs. non-energy goods	0.8
	Non-energy good vs. non-energy good	1
	Energy good vs. energy good	1
Substitution elasticities in government demand		
σ_G	Fossil fuel vs. fossil fuel	0.8
	Fossil fuels vs. non-fossil fuels	1
	Non-fossil fuel vs. non-fossil fuel	1
Elasticities in international trade (Armington)		
σ_A	Substitution elasticity between imports vs. domestic inputs	4.0
ε	Transformation elasticity domestic vs. export	4.0

Allen elasticities of substitution for the Cobb-Douglas function in cost prices in the CGE model for each sector are given by

$$\sigma_{ij} = 1 - \frac{P_i \cdot P_j}{w_i \cdot w_j} \cdot \left[\sum_k \frac{(\gamma_k + b_k \cdot t) \cdot \alpha_{ik} \cdot \alpha_{jk}}{\widetilde{P}_k^{\,2}} \right] \qquad i, j, k = \text{K,L,E,F,M.}$$

The price elasticities of demand for factors of production (ε_{ij}) are $\varepsilon_{ij} = \sigma_{ij}\, w_j$. Table 7.7 presents these elasticities.

Table 7.7 Allen elasticities of substitution and price elasticities of demand

Sector	OTH	EIS		OTH	EIS
σ_{KL}	0.996	0.993	ε_{KL}	0.153	0.097
σ_{KE}	0.997	0.999	ε_{KE}	0.011	0.036
σ_{KM}	0.999	0.999	ε_{KM}	0.489	0.647
σ_{KF}	0.996	0.998	ε_{KF}	0.011	0.032
σ_{LE}	-2.181	0.009	ε_{LK}	0.333	0.185
σ_{LM}	0.444	0.580	ε_{LE}	-0.024	0.0003
σ_{LF}	-3.035	-0.432	ε_{LM}	0.217	0.375
σ_{EM}	0.579	0.937	ε_{LF}	-0.035	-0.014
σ_{EF}	-2.053	0.786	ε_{EK}	0.334	0.187
σ_{MF}	0.466	0.909	ε_{EL}	-0.334	0.001
ε_{KK}	-0.664	-0.812	ε_{EM}	0.283	0.607
ε_{LL}	-0.491	-0.547	ε_{EF}	-0.024	0.025
ε_{EE}	-0.259	-0.820	ε_{MK}	0.335	0.187
ε_{MM}	-0.414	-0.306	ε_{ML}	0.068	0.056
ε_{FF}	-0.073	-0.761	ε_{ME}	0.006	0.034
			ε_{MF}	0.005	0.029
			ε_{FK}	0.333	0.186
			ε_{FL}	-0.465	-0.042
			ε_{FE}	-0.023	0.028
			ε_{FM}	0.228	0.589

* The calibrated parameters are $\gamma_{L_{EIS}}$ = 0.151 and $\gamma_{L_{OTH}}$ = 0.238. The benchmark value shares for Germany are $w_{K,EIS}$ = 0.187, $w_{L,EIS}$ = 0.097, $w_{E,EIS}$ = 0.036, $w_{M,EIS}$ = 0.648, $w_{F,EIS}$ = 0.032, $w_{K,OTH}$ = 0.335, $w_{L,OTH}$ = 0.153, $w_{E,OTH}$ = 0.011, $w_{M,OTH}$ = 0.489 and $w_{F,OTH}$ = 0.011.

8 Technological Change in E3 Models[*]

8.1 Introduction

The threat of climate change, potentially produced by the growing accumulation of greenhouse gases (GHG) in the atmosphere, has led to an increasing number of empirical models for climate change policy analysis. Numerous modeling studies have shown the sensitivity of mid- and long-run climate change mitigation cost and benefit projections to assumptions about technology (EMF, 1996). Technological change (TC), that is increases in outputs without increases in productive inputs, can lower the cost of GHG abatement policies through product innovations, i.e. higher energy-efficiency of existing and new products, and process innovations, i.e. higher energy efficiency of manufacturing processes, cost reductions in low-emission energy conversion and improvements in fossil energy conversion. Technological change is in general considered to be a non-economic, exogenous variable in energy-economy-environment (E3) models. Economic activities and policies have then no impact on research, development, and diffusion of new technologies. The emphasis is placed upon showing the mere effect of technical change, but not on how technology development occurs. However, there is overwhelming evidence that technological change is not an exogenous variable, that can be simply defined outside the model, but to an important degree endogenous, induced by needs and pressures (Grubb et al., 1995). Especially over the longer time horizon typical for climate policy analysis, models incorporating induced technological change may project total costs of abatement that are substantially lower than those reported by conventional models with exogenous technical change. Hence, a new generation of environmental-economic models treats technological change as endogenous, i.e. responding

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[*] This chapter is based on the paper ‘Technological Change in Economic Models of Environmental Policy: A Survey’, in: *Ecological Economics*, 43, 105-126, 2002.

to socio-economic (policy) variables, e.g. prices, investment in R&D, or cumulative production. This approach is much more difficult than the conventional approach, since the processes of technical change are complex and empirical understanding of the determinants of technological change is still lacking.

Schumpeter (1942) distinguishes three stages in the process of technological change. Invention of a new product or process; innovation, which is the transformation of an invention into a commercial product, accomplished through continual improvement and refinement of the new product or process; diffusion, which is the process of gradually adoption of the innovation by other firms or individuals from a small niche community to being in widespread use. The technological change process is usually initiated by a public or private investment activity called research and development (R&D) in the subsequent phases of invention and innovation. The output of the R&D activities is an intangible asset to the firms, 'knowledge capital', which is used together with other inputs to generate revenues. The magnitude and direction of corporate investment in the knowledge sector is governed by private profit incentives from (at least partly) appropriable innovations. However, it is difficult to exclude others from knowledge embodied in an industry's innovation. It contributes to the innovation process of other industries and results in knowledge spillovers, or positive externalities, to competing firms (Griliches, 1979). The diffusion of new, economically superior technologies is never instantaneous, but typically follows an S-shaped (sigmoid) curve that measures the rate of diffusion of innovations over time (Rogers, 1995). The fraction of potential users that adapt the new technology rises only slowly in the early stage, then gets faster, then slows down again as the technology reaches maturity and approaches saturation. Experience with a technology leads to a gradual improvement over time as a function of learning processes: learning in R&D stages, learning at the manufacturing stage ('learning-by-doing') and learning as a result of use of the product ('learning by using') (Rosenberg, 1982).

Economists probe for deeper understanding of what goes on insides the 'black box' of technology (Rosenberg, 1982). According to the Schumpeterian view of invention and innovation as a purposive economic activity, there are three major traditions regarding the sources of technical change (Ruttan, 1997). The (neoclassical) *induced innovation approach* suggests that the rate and direction of innovation responds to changes in demand and relative factor prices. The 'demand pull' model (Griliches, 1957; Schmookler, 1966) emphasizes the importance of change in market demand on the supply of knowledge and technology. The microeconomic investment model builds on an early observation by Hicks: ‘a change in the relative prices of factors of production is itself a spur to innovation and to inventions of a particular kind – directed at economizing the use of a factor which has become relatively expensive’ (Hicks, 1932, pp. 124-125). The *evolutionary approach* is inspired by Schumpeter’s insights into the process of economic development (Nelson and Winter, 1982). Firms engage in satisficing rather than optimizing economic behavior and use ‘routines’ e.g. for production activities, personnel action, determination of production mix, research and development. The activities that lead to technological change in the evolutionary approach are local searches for technical innovations and imitation of practices of other firms. Since firms are not optimizing, ‘win-win’ outcomes from environmental regulation in which pollution is reduced and profit increased (Porter and van der Linde, 1995) are possible in the evolutionary model. These models have been complemented by the development of the historically grounded *path dependence approach* to technical change (Arthur, 1989, 1994; David, 1985). Products or systems subject to increasing returns to scale (positive feedbacks) are path-dependent, i.e. a sequence of micro-level historical events influences future possibilities. Increasing returns are linked with inflexibility (once a dominant technology begins to emerge it becomes progressively more ‘locked in’) and non-ergodicity (historical small events may decide the outcome). Lock-in implies that once a particular (potentially inefficient) technological path is led down, it is difficult (prohibitive) to move to an alternative competing path.

The aim of this chapter is to provide an overview of how exogenous and induced technological change is represented in applied energy-economy-environment models, and what implications the different specifications have for modeling results. Virtually all studies of induced technological change in environmental economics have been theoretical (e.g. Bovenberg and Smulders, 1995). But since the effects of environmental policy on the rate and direction of technological change and, particularly, the costs of reducing GHG emissions cannot be resolved at a purely theoretical level, there is a need for empirical analyses. Section 8.2 gives a taxonomy of different model types (bottom-up, top-down, integrated assessment models). Section 8.3 explores exogenous specifications of technical change, such as the autonomous energy efficiency parameter, the specification of backstop technologies and technology snapshots. Section 8.4 discusses different approaches to incorporate endogenous technical progress in applied models. Even though the theory of endogenous technological change is still in development at present, three main elements in models of technological innovation can be identified: (i) corporate investment in research and development (R&D) in response to market conditions, (ii) spillovers from R&D and (iii) technology learning, especially learning-by-doing (LBD). While the first element is linked to the induced innovation approach, the last element is linked to the path dependence approach to technological change. Section 8.5 shows the complexity associated with the incorporation of endogenous technological change and how well-known economic models of climate change account for technical change. Section 8.6 summarizes the quantitative results obtained from modeling exercises and the implications of different specifications of technological change. Section 8.7 suggests different model extensions and concludes.

8.2 Modeling Approaches: Bottom-up vs. Top-down

Models of complex socio-economic systems require simplifying assumptions on system boundaries and system relationships. They operate under the assumption that the underlying economic structure will remain unchanged, or else it will change in a specified way. Technological change can be integrated to economic models of climate change as it relates to this assumption. There are two broad approaches for modeling the interaction between energy, the environment and the economy (see Section 2.2.1.2). They differ mainly with respect to the emphasis placed on a detailed, technologically based treatment of the energy system, and a theoretically consistent description of the general economy. The models placing emphasis on the former are bottom-up engineering-based energy system models (ES), lacking interaction with the rest of the economy. Bottom-up models embed new technologies and model the penetration of these technologies based on costs and performance characteristics. Technological change occurs as one technology is substituted by another.

The models emphasizing the above-mentioned description of the general economy are top-down general economic models with only rudimentary treatment of the energy system. They describe the energy system in a highly aggregated way by means of neoclassical production functions. They usually do not rely on direct descriptions of technologies. Technological change, rather, alters the costs of production at a commodity or industry level.

CGE models and macroeconometric models (ME) are top-down models. Macroeconometric models are based on long-run time series data. They consist of econometrically estimated equations without equilibrium assumptions. Macroeconometric models offer a lot of economic detail, but little structural detail. Because of their structural features, they are especially suited for short-run or medium-run evaluation and forecasting. There are also various mixes of these broad types. Sometimes a top-down representation of the economy is linked with a bottom-up description of technologies in energy markets (Manne, 1981). A synthesis of bottom-up and top-down modeling with a direct technology description in the energy sectors and top-down regular functional forms in the other production sectors is presented by Böhringer (1998b).

Models for the integrated assessment of climate protection strategies, i.e. Integrated Assessment Models (IAMs), currently try to approach climate change modeling in a very comprehensive way, by gathering knowledge from diverse scientific fields. Economic models are combined with environmental or climate change sub-models. IAMs are divided into two broad categories, which vary according to the policy options available to the regulator. Policy evaluation (or simulation) IAMs evaluate the effect of an exogenous policy on biosphere, climate and economic systems. In contrast, policy optimization IAMs have the purpose of finding the efficient or cost-efficient climate change policy and simulating the effect of an efficient level of carbon abatement. Since this is a complex process, such models typically have relatively simple economic and climate sectors (IPCC, 2001).

Since top-down models are based on behavioral relations they are well suited for the analysis of long-term innovation. In addition, they provide a consistent framework for the assessment of knowledge accumulation and technology spillovers between different sectors. In contrast to bottom-up models, rebound effects (Binswanger, 2001) linked to the introduction of a new technology - reduced energy prices stimulate consumption - are fully integrated. Technological change in top-down models is described through the relationship of inputs and outputs. Existing technologies are gradually replaced as relative prices of alternative technologies change. Changes in technologies are the result of price substitution along a given production isoquant (described by price elasticities) and shifts of the isoquant through changes in factor demand. In contrast, technological change in bottom-up models often occurs through the sudden penetration of new technologies (snapshot technologies). New technologies are adapted rapidly, or even instantaneously, in optimizing models, because they have higher efficiencies. The rate of overall technical change depends on the difference between snapshots and the pace of adoption (Edmonds et al., 2000). Absolute shifts in bottom-up models neglect transaction costs, inertia in the energy system and market failures on the demand side (e.g. information costs, high discount rates) and thus yield too optimistic cost estimates. The same is true for the inclusion of backstop technologies in top-down models. Even though the specific class of a model is important for GHG mitigation cost projections, recent model studies show that the different modeling approaches are less important than model differences in assumptions about cost and baseline definition, producer and consumer flexibility and the depiction of technological change dynamics (Hourcade and Robinson, 1996; Weyant, 2000). Indeed, the difference in the descriptions of technological progress seems to be the most important explanation for the inequality between top-down and bottom-up models in the assessment of economic costs of GHG emissions (Carraro and Galeotti, 1997).

8.3 Exogenous Specification of Technological Change

Basically all models of climate change agree with Solow (1956) in assuming an exogenous overall productivity growth of about 2-3 percent per year (Azar and Dowlatabadi, 1999). In addition, exogenous technological change can be introduced to any economic model of climate change by an autonomous energy efficiency (AEEI) parameter or by assumptions about future costs of energy technologies (backstop). Modelers have to make assumptions about parameter values in the former case, while they make direct assumptions about the technology in the latter.

8.3.1 Autonomous Energy Efficiency Improvement

The decoupling of economic growth and energy use is commonly represented by an exogenous parameter referred to as the autonomous energy efficiency improvements (see e.g. Manne and Richels, 1992; Nordhaus, 1994). The AEEI is a heuristic measure of all non-price driven improvements in technology, which in turn affect the energy intensity. It may be constant or follow some estimated non-linear time trends. The use of constant AEEI terms in energy-economy modeling follows the assumption that the innovation of new energy technologies is related to a large number of minor improvements which come mostly from applying results from the common, gradually evolving pool of knowledge (Jacobsen, 2001).

The AEEI parameter may either represent structural changes in the economy, i.e. changes in the share of energy in total economic output over time, or sector specific technological change, i.e. changes in the energy use per unit output of an industry through time. It is simply included as a separate coefficient in the production or cost functions of the models (factor augmenting or price diminishing technical change). A constant-elasticity-of-substitution (CES) unit cost function (*c*) with exogenous price diminishing technical change for input *i* (γ_i, $\gamma_i > 0$) is given by:

$$c = \sum_i \left[\delta_i \left(p_i \cdot e^{-\gamma_i \cdot t} \right)^{1-\sigma} \right]^{1/1-\sigma}, \tag{8.1}$$

where δ is the distribution parameter, σ is the substitution elasticity, t indexes time, and p_i is the input price. Due to the price effects of the energy efficiency improvement, the AEEI parameter reduces the energy-output ratio in CES production functions only if the substitution elasticity is less than unity (Kemfert and Welsch, 2000).

Of course, changes in energy (carbon) intensity are also determined by the responsiveness of energy demand to changes in energy prices, i.e. the price elasticity of the demand for energy, and simple price-induced factor substitution. As the relative price of energy increases, e. g. in response to climate change policies to reduce GHG emissions, consumers and firms substitute inputs away from energy and towards others (e. g. increased use of labor instead of machines, or public transport instead of privately owned vehicles, see Mabey et al., 1997). The degree to which capital or labor can be substituted for energy is determined by the elasticity of substitution between energy and these factors, creating thus another important parameter for the development of energy intensity in global models. The carbon intensity is additionally determined by the substitution possibilities among fossil fuels (e. g. switching from coal to gas for electricity generation). However, the changes in demand for production inputs with relative prices represent choices among policy options already available. In contrast, the AEEI improves the technology available to the producers (and the consumers) and alters the production function itself. The main problem when including technical progress with the AEEI is the difficulty to distinguish between technical progress and long-term price effects (Jones, 1994).

8.3.2 Backstop Technologies

Another approach to include technical progress used in many macroeconomic models is the incorporation of exogenously provided discrete new technologies. These backstop technologies are energy sources that are already known, but not yet commercial. Since the price mechanism determines the production technology used, backstop technologies come into play as, on the one hand, they mature and costs fall with technological progress and, on the other hand, production costs of conventional technologies rise, either due to the depletion of conventional energy resources or environmental policies and associated prices increases. It is commonly assumed that a backstop technology is available in unlimited supply at a constant - and usually relatively high - marginal cost, i.e. price of the backstop. The high costs of the backstop technologies reflect the associated costs of R&D investments. The upper limit to which energy prices increase is then given by the production cost of the speculative future technologies. Backstop technologies eliminate the effect of increasing energy costs reported by other models. In long-term model projections, backstop technologies often provide a large percentage of global energy by the middle of the century. Consequently, the assumed availability and cost of backstop technologies have important impacts on model outcomes (Manne and Richels, 1994). Energy-economic models typically include either or both fossil and non-fossil backstop technologies. Backstop technologies are sometimes purely generic, synthetic technologies. Sometimes they are more fully specified or existing technologies. Examples are carbon-free electric power generation with solar power technologies such as photovoltaic or fuel cells, ethanol from biomass, nuclear fusion, and advanced fossil fuel generation technologies such as shale oil (see, for instance, Manne and Richels, 1992, 1999; Peck and Teisberg, 1992, 1999; Babiker et al., 2001).

Backstop technologies in macroeconomic models are a special form of so-called ‘technology snapshots’. Technology snapshot models describe in considerable detail future available technologies. Particularly bottom-up engineering models specify many alternative technologies for energy production. This can be also done in hybrid top-down and bottom up models (Böhringer, 1998b). The different technology snapshots substitute each other according to some economic criteria over time (Edmonds et al., 2000). Discrete technology choice models make assumptions about the technological diffusion, i.e. assumptions about the degree of penetration for existing technologies together with assumptions on individual technological progress. Exogenous technological change, specified in one of these ways, is able to assess the effects of replacing the existing capital stock with more energy efficient technologies, i.e. the effect of technical progress, but it can not model aspects like innovation or diffusion. Especially, it can not consider technologies potentially developed in the future.

8.4 Endogenous Specification of Technological Change

8.4.1 Investment in R&D

A newer class of modeling approaches treats innovation as a product of explicit investment in research and development. This approach is inspired by macro models of induced technological change (Lucas, 1988; Romer, 1990; Grossman and Helpman, 1994). The new growth theory builds on the recognition that technological innovation is an economic activity. It arises from the efforts of profit-maximizing agents within the economy and is an endogenous response to Schumpeterian profit incentives. Knowledge is explicitly treated as non-rival and not (fully) appropriable. Investment in R&D generates spillovers, or positive externalities, which allow an economy to grow infinitely. These implications of the new growth theory for technological change and long-run economic growth stand in contrast to conventional neoclassical growth models with exogenous technical change and decreasing returns to investment in physical capital in which income per capita does not grow in the steady-state. In the new growth theory literature, endogenous technological change focuses on neutral technological change and aggregate R&D expenditure, while induced technological change focuses on the direction of R&D efforts and biases in technological change (Jaffe et al., 2000). The induced innovation hypothesis with direct modeling of investment in innovation or knowledge is present in only a few climate change models.

Goulder and Mathai (2000) use a partial equilibrium model of knowledge accumulation in which a firm chooses the time paths of abatement and R&D investment that minimize the costs of achieving a certain emission target. Induced technological progress is incorporated in the abatement cost function (*C*) that depends on the level of abatement (*A*) and on the stock of knowledge (*H*) (cost-function model). Knowledge accumulation and thus technological progress may either be R&D based or based on learning-by-doing (LBD) in carbon abatement. In the first case, the evolution of the knowledge stock is described by:

$$\dot{H}_t = \alpha_t H_t + k\Psi\left(I_t, H_t\right), \tag{8.2}$$

where I is investment in knowledge, i.e. R&D expenditure, α is the rate of autonomous technological progress and Ψ is the knowledge accumulation function. The evolution of the knowledge stock in the latter case is given by:

$$\dot{H}_t = \alpha_t H_t + k\Psi\left(A_t, H_t\right). \tag{8.3}$$

The parameter k describes whether R&D-based or LBD-based induced technological progress is present. While knowledge accumulation is costly in the R&D-based case, it is free in the LBD-based representation.

Nordhaus (1999) and Buonanno et al. (2001) describe the endogenous reaction of innovations in different sectors to price variations (or regulation) in a neoclassical optimal growth framework (the RICE model). The economic agent chooses the optimal level of investment and R&D effort. R&D is the source of technical change. Resources directed to R&D improve the state of knowledge (called ‘innovation’). The innovation-possibility frontier, i.e. the production function for new knowledge, is given by a constant-elasticity function of the level of research in the sector. This function is calibrated to empirical studies of the inventive process. It is assumed that current innovations build on past innovations (‘building on shoulders’ model of innovation). There are diminishing returns to inventive activity in the particular period but the innovation possibilities are replenished in the next period.

Nordhaus (1999) adds an energy/carbon input to the DICE Cobb-Douglas production function. The rate of energy efficiency improvement varies with the amount of additional R&D expenditure in the energy sector. Carbon abatement in this framework is either due to induced technological change or factor substitution. Buonanno et al. (2001) describe economic output (Q) as a function of the stock of knowledge capital (K_R), physical capital (K) and labor (L):

$$Q = A \cdot K_R^{\beta} \cdot \left(L^{\gamma} \cdot K^{1-\gamma} \right), \tag{8.4}$$

where A indicates exogenous technological change. Since the stock of knowledge is a factor of production, changes in knowledge capital through R&D efforts raise the productivity of resources and result in non-environmental technical progress. As long as the output elasticity of knowledge β is positive, the production will be characterized by increasing returns to scale, i.e. by endogenous technological change as referred to by the new growth theory. In addition, the knowledge stock affects the emission-output ratio (E/Q):

$$\frac{E}{Q} = \left[\sigma + \chi \cdot e^{-\alpha \cdot K_R} \right] \cdot (1 - \mu), \tag{8.5}$$

where σ is an exogenous parameter describing the technology in abatement, μ is the rate of abatement effort and α describes the elasticity of the emissions-output ration with respect to knowledge capital. As long as the scaling coefficient χ is positive, R&D efforts will also result in induced environmental technological change in form of an improvement in energy-efficiency, i.e. a reduction in the influence of energy and carbon inputs on output. Thus, R&D and increased knowledge extend the productivity of the firm and reduce the negative impact on the environment.

Another economy-wide analytic approach to model induced technical change in greenhouse gas abatement is given by Goulder and Schneider (1999). They construct a dynamic general equilibrium model in which firms in each sector employ labor, physical capital and knowledge capital, fossil-based (conventional) and non-fossil based (alternative) energy, energy-intensive materials and other materials to produce output. Induced technological change is achieved – similar to (8.4) – through a shift term in the neoclassical production functions that is influenced by the industries' R&D. Investment in new physical capital and expenditure on R&D activities expand the respective capital stocks. Knowledge accumulation reduces the input requirements for the industries. The accumulation of knowledge is costly. The model considers the connections between the demand and the supply of R&D and, accordingly, of the scarce knowledge-generating resources (e.g. labor), the rate of technological change and the policy initiative. Goulder and Schneider emphasize the importance of accounting for opportunity costs of inducing technological change, i.e. the costs of redirecting R&D resources from one sector to another. An increase in conventional fuel prices in response to a carbon tax increases the markets for carbon free technologies and creates an incentive for increased R&D in these sectors. This induce technical change thus lowering the costs of carbon free technologies. But increased investment in R&D by one sector reduces investment in R&D by other sectors since it demands scarce knowledge-generating resources (crowding-out). Rapid technological change in one sector will thus be accompanied by less rapid technological progress in other industries.

8.4.2 Spillover Effects

Spillover effects from investment in R&D, or positive technological externalities, provide the source for long-term growth in the macro-level new growth theory. Empirical studies demonstrate the significance of spillovers (Griliches, 1992). With external economies, the social rate of return exceeds the private rate of return on investment in R&D. There is evidence that research has a social return of 30 to 70 percent per annum as compared to private returns on capital of 6 to 15 percent per annum (Nordhaus, 1999). The fundamental role of spillovers makes their incorporation in the modeling of induced technological change imperative. However, in firm-level innovation theory, spillovers affect investment incentives prior to innovation, since innovations are not fully appropriable with spillovers. In this framework, spillover effects are no longer strictly positive externalities. Since the underlying mechanisms of innovation and spillovers are currently incompletely understood, Weyant and Olavson (1999) suggest the use of spillovers only as a heuristic modeling tool that accounts for the macro-level observation. Appropriability and spillovers should be separated: Firms invest in R&D given some expected approbiability of knowledge as described in the previous section. Spillovers are overlaid on this models as an add-on, strictly positive feature resulting from previous investment decisions. The level of investment in R&D is then governed by private investment incentives, but the rate of innovation with spillovers may be higher than the respective rate without. Spillovers may be intrasectoral or intersectoral, local or international.

Goulder and Schneider (1999) introduce knowledge spillovers to an individual firm in an industry by a scale factor (γ) in a CES production technology that is an increasing function of (non-excludable) spillover knowledge enjoyed by all firms (H):

$$X = \gamma(H) \cdot \left(N^{\rho} \cdot G^{\rho}\right)^{1/\rho}, \tag{8.6}$$

where X is output, N is appropriable knowledge, G is an aggregate of all other production inputs and ρ is the substitution parameter. The spillover benefit is given by

$$H_{t+1} = H_t + \beta R_t, \tag{8.7}$$

where R is the industry-wide expenditure on R&D and β shows the magnitude of potential spillovers. It is assumed that firms regard H as exogenous.

Buonanno et al. (2001) account for international knowledge spillovers by introducing the stock of world knowledge ($K_W = \sum K_R$) both in the production function and in the emissions-output ratio of the DICE model:

$$Q = A \cdot K_R^{\beta} \cdot K_W^{\varepsilon} \cdot \left(L^{\gamma} \cdot K^{1-\gamma}\right), \tag{8.8.4'}$$

$$\frac{E}{Q} = \left[\sigma + \chi \cdot e^{-\alpha \cdot K_R - \theta \cdot K_W}\right] \cdot (1-\mu). \tag{8.8.5'}$$

This spillover modeling takes into account that technologies and institutional structures diffuse internationally as the world economies are increasingly linked through international trade, capital flows, and technology transfers. With spillovers, each region learns from the knowledge (technology) of the rest of the world. Advanced technologies developed in industrialized countries are gradually adopted by developing countries. Multi-regional top-down models that account explicitly for international trade flows are – in contrast to bottom-up models – generally well suited to assess these effects of geographical diffusion of new technologies (Botteon et al., 1994).

8.4.3 Technology Learning

Initial installations of technological innovations are often expensive. Costs decline as individuals, enterprises and industries gain experience with them. The learning or experience curve describes technological progress as a function of accumulating experience with the production (learning-by-doing for manufacturers) and the use (learning-by-using for consumers) of a technology during its diffusion. Technological learning has been observed historically for many different industries and is a well-established empirical concept. Several authors suggest learning curves as a meaningful presentation of technological change in global energy models (e.g. Azar and Dowlatabadi, 1999; Grübler et al., 1999). Learning-by-doing in technologies or systems as a source of technical change was first emphasized by Arrow (1962). The Boston Consultancy Group (1968) established the experience curve concept, relating total costs and cumulative quantity. It takes into account all parameters that influence the total costs of a product such as production improvements (process innovations, learning effects and scaling efforts), product development (product innovation, product redesign, and product standardization), and decreases in process input costs (Neij, 1997; IEA, 2000) and traces them through technological and product evaluation. Kline and Rosenberg (1986) show that technology learning may have a larger impact on technological progress than the initial process of development itself.

In the basic model with a learning mechanism, technological progress is expressed in terms of decreasing specific costs of a technology (*C*) as a function of cumulative (installed) capacity (*K*). The cumulative capacity is used as a measure of the knowledge accumulation that occurs during the manufacturing (learning-by-doing) and the use of the technology (learning-by-using) (Christiansson, 1995). A commonly used learning-by-doing function is:

$$C = \alpha \cdot K^{-\beta}, \tag{8.8}$$

where α is a normalization parameter and β is the learning elasticity (or learning index) (Anderson, 1999). With this definition, every doubling of total installed capacity reduces specific costs by a factor of $2^{-\beta}$. This factor is also called progress rate (PR) and defines the speed of learning. The complementary learning rate (LR = 1 - PR) gives the percentage reduction in the specific capital cost of newly installed capacity for every doubling of cumulative capacity. A recent overview of experience accumulation and cost reduction for a number of energy technologies is given by McDonald and Schrattenholzer (2001). Learning rates for different energy technologies given by IEA (2000) are summarized in Table 8.1. The variation is significant; there must be a 19-fold increase in the cumulative installed capacity for biomass, but only a 3-fold increase for photovoltaics in Europe for a 50 percent reduction in costs. Accordingly, the time span until the new technologies become competitive differs considerably.

Table 8.1 Learning rates for energy technologies (in %) *

Energy technology	Europe	USA	Elsewhere
Photovoltaics	35	18	-
Wind power	18	32	-
Biomass (electricity)	15	-	-
Ethanol production	-	-	20
Supercritical coal	3	-	-
Natural gas-fired combined cycle	4	-	-

* IEA (2000) and own calculations.

Technology learning often shows different phases (Mackay and Probert, 1998). In the research, development and deployment phase (RD&D), high learning rate can usually be observed as technologies first seek a market niche. In the commercialization or diffusion phase, learning rates are lower. When market saturation is reached, the learning rate may fall close to zero and technology learning is hardly noticeable (IEA, 2000). To avoid both overestimation and underestimation of the future progress ratios, the different phases of technologies must be taken into account when extrapolating historical data. Photovoltaics (mostly module) have had a learning rate of roughly 20 percent since 1975. This is also true for wind and gas turbines in their research, development and deployment phase. However, gas turbines show a learning rate of about 10 percent in the commercialization phase. The learning rates of technologies, such as photovoltaics, may also fall to 10 percent when the technology and market mature (UNDP, 2000).

8.4.4 Other Approaches

There have been a number of other ad hoc attempts to model technological change. Since technological progress cannot be observed directly, various econometric studies infer technological change by observing the dynamics of other variables (latent variable approach). The estimation equations describe the economic mechanism through which economic variables affect technical progress. Technical progress in this approaches is non-autonomous, but not explicitly modeled as the outcome of optimizing behavior of economic agents. Rather, technical change is often modeled as an empirical function replacing the deterministic AEEI as a proxy of technological change. The advantage is that all types and sources of technological development are included in these models (Weyant and Olavson, 1999). However, since the empirical models build on historical data, they are suitable only for short- or medium term cost assessments.

Dowlatabadi and Oravetz (1997) and Dowlatabadi (1998) construct a model of price-induced energy efficiency. The empirical analysis of the historical rate of technical change embodied in the AEEI parameter showed that it has been strongly influenced by energy price changes over the period from 1954 through 1994. The assumption of a deterministic technical progress may thus not be correct for long periods of time. They replace the exogenous AEEI by an energy efficiency response model of induced technological change that reacts to energy prices. In the period of declining energy prices up to 1974 the price induced energy efficiency improvement (PIEEI) was about –1.6 percent, but only about 1 percent in the period of rising energy prices thereafter. This confirms the intuition that price increases spur greater innovation and a greater diffusion of energy-saving technologies. Empirically, the linkage of efficiency improvement to energy prices demands a distinction between price-induced shifts in factor inputs and price-induced improvements of efficiency, which is difficult to establish.

Jorgenson and Wilcoxen (1990) present the most complete empirical model of endogenous technological change. They include technological progress by allowing input prices to interact with a time trend. For each industry, they use a translog unit cost function (c_i) in which costs depend on the prices of all inputs (p_j) and an autonomous technological (time) trend (t):

$$\ln c_i\left(p,t\right) = \alpha_o^i + \sum_j \alpha_j^i \cdot \ln p_j^t + \alpha_T^i \cdot t + \frac{1}{2}\sum_j \sum_k \beta_{jk}^i \cdot \ln p_j^t \cdot \ln p_k^t + \sum_j \gamma_{jT}^i \cdot t \cdot \ln p_j^t + \frac{1}{2}\delta_{TT}^i \cdot t^2 . \quad (8.9)$$

The input coefficients are derived by Shephard’s lemma. They vary to implicitly capture the effects of induced technological change:

$$\frac{x_{ji}}{x_i} = \left(\alpha_j^i + \sum_k \beta_{jk}^i \cdot \ln p_k^t + \gamma_{jT}^i \cdot t\right) \cdot \frac{c_i}{p_j} . \quad (8.10)$$

Differentiating the cost function with respect to *t* shows the components of technical progress:

$$\frac{\partial \ln c}{\partial t} = \alpha_T^i + \sum_j \gamma_{jT}^i \cdot \ln p_j^t + \delta_{TT}^i \cdot t . \quad (8.11)$$

The exogenous parameters α_T and δ_{TT} represent the neutral component of technical progress. Technical progress becomes endogenous because of the second term. An increase in the price of input *i* reduces cost reduction due to productivity growth if the bias of technical change is input *i* using ($\gamma_{iT} > 0$). Hence, price induced productivity growth partially endogenizes technological development (‘factor price bias’). Jorgenson and Wilcoxen statistically estimated productivity growth for 35 industries from observed changes of input prices and the index of technology using extensive time series data on inter-industry transactions from 1947 to 1985. Different industries exhibit different rates of technical change. They found energy saving technical change ($\gamma_{iT} < 0$) only for three industries. The approach is often called semi-endogenous, since it does not really endogenize technical change. Biased productivity growth, γ_{iT}, is still exogenous and there is no explicit explanation for the assumed relationship.

Another approach to incorporate technical change in environmental models is the use of macroeconometric vintage models with capital vintages involving different technologies (Solow, 1959). These technologies may have effects on the production function, the input structure (energy efficiency), or the flexibility of the vintage. For example, substitution possibilities among inputs of production may be higher with new vintages than with old vintages (Bergman, 1990; Burniaux et al., 1992), or the parameterization of each vintage’s cost function may differ (Conrad and Henseler-Unger, 1986). Hence, with different vintages, the input structure not only depends on the substitution possibilities for the vintages when relative prices change but also on the input structure of the new vintage and the rate at which new investment goods disperse into the economy. If new capital brings better technology, then productivity should rise as capital investment accelerates and as the average age of the capital stock declines. Disembodied technical progress in the vintage concept comes from adjusting, for example, an energy coefficient by the decay of old vintages and by adding the input coefficient of the new vintage. The price dependent input coefficient for energy based on the new relative prices in the following period is

$$\frac{E_{t+1}}{X_{t+1}} = \frac{1}{1+g}\left[(1-\delta)\cdot\alpha_t^{\sigma}\cdot\left(\frac{PE_{t+1}}{PX_{t+1}}\right)^{-\sigma} + (g+\delta)\cdot\beta_t^{\sigma}\cdot\left(\frac{PE_{t+1}^{NVK}}{PX_{t+1}}\right)^{-\sigma}\right], \tag{8.12}$$

where δ is the rate of capital depreciation, g is the growth rate of output, X is the output with price PX, E is the energy input, PE and PE^{NVK} are the energy prices associated with the respective vintage, and α and β are distribution parameters for energy of the old and new production process, respectively (Conrad, 2001). Currently, there are many established vintage models, either macroeconometric models, dynamic general equilibrium models or technically based bottom-up models. However, the vintage approach that embodies technological progress in each year's capital vintage is - except for the pace and the size of capital investment - again an exogenous specification of technological progress.

Lee et al. (1990) incorporate induced technological change following the neo-Keynesian approach by using Kaldor's technical progress function that links productivity growth and capital accumulation (Kaldor, 1957). Technological progress (T_t) simply follows a recursive relationship with gross investment and R&D expenditure:

$$T_t = \alpha_o + \alpha_1 \cdot d_t, \tag{8.13}$$

$$d_t = \beta d_{t-1} + (1-\beta)\cdot \ln\left(I_t + \gamma RD_t\right). \tag{8.14}$$

In these equations, α_0 and α_1 are constants, β measures the impact of past quality-adjusted investment on the current state of technical advance (i.e. R&D and gross investment form a technological index designed to represent the stock of knowledge accumulated over time), γ is a weighting parameter for R&D expenditure, I is gross investment, and RD is R&D expenditure. However, this very simplistic modeling of endogenous technological change has no microeconomic underpinning (Grubb and Köhler, 2000).

Carraro and Galeotti (1996, 1997) infer technological progress from the dynamics of the capital stock (K), which is split into an energy-saving one (K_e) and an energy consuming one (K_p). A new vintage of the capital stock is added to the two components each year. The growth rate of the total capital stock (g) is given by:

$$g = g_p + \left[g_e - g_p \right] \cdot \frac{K_e}{K}, \tag{8.15}$$

where g_e and g_p are the growth rates of the different capital stocks that are econometrically estimated. The amount of R&D carried out by firms is endogenously determined by relative prices, market demand, and policy variables such as environmental taxes or R&D subsidies. R&D activities affect the firms' decision to install energy-saving capital and, thereby, the composition of their capital stock. An increase in R&D expenditure is likely to produce investment in environment-friendly capital. The ratio of the stock of the environmental friendly capital to polluting capital is used as an indicator of technological progress. That is, there is a quantified relationship between R&D and technological progress. It should be noted, however, that most of the observed increase in energy efficiency is not related to the choice between energy extensive and energy intensive capital.

8.5 Incorporation of Technological Change

This section describes the methodological and computational complexity associated with the incorporation of endogenous technological change and surveys recent developments in technological modeling within energy-economy-environment models. Since the different models are designed for different objectives, there is no single way to incorporate the different approaches to technological change in the different model types.

8.5.1 Methodological and Computational Complexity of Technological Modeling

Most energy-economy-environment models rely on diminishing returns that generate negative feedbacks which tend to stabilize the system. These convex models generally lead to a unique solution independent of the initial state of the economy. In contrast, economic processes with externalities and increasing returns to scale lead to positive feedbacks which tend to destabilize the system. Introducing endogenous technical change makes the models highly non-linear systems with path dependencies and the potential for multiple equilibria. Increasing returns to scale might lead to the magnification of chance events as adoption takes place (non-predictability), the adoption of long-run inferior technologies (potential inefficiency), the lock-in of technologies (inflexibility) and the determination of technology dynamics by historical 'small events' (non-ergodicity) (Arthur, 1994). The endogenous specification of technological change as described in the previous section thus depends crucially on the assumptions about the exogenous parameters.

Climate policy seems highly sensitive to lock-in phenomena and path-sensitivity (Grubb et al., 1995; Ha-Duong et al., 1997). The lock-in effect is mainly determined by direct investment costs, as in the case of learning, but also by other considerations, such as uncertainty or infrastructure and networks that create de facto standards for a technology (Arthur, 1989). Firms may find it more profitable in the short run to invest in technologies that are already competitive, or, given high rates of technical change, investors may just wait and see. Hence, many innovations never reach commercialization even though they are potentially superior to existing, established alternatives. These behavioral and strategic issues lead to a highly path-dependent technology adoption and a path of technological change that evolves with a great deal of inertia.

The non-convexities in the dynamics of technical change significantly increase the computational complexity. Either there may be no unique optimum or multiple equilibria may occur in many different directions. These are general features of systems with increasing returns to scale. Standard optimization techniques are not applicable in this case, since using a standard algorithm for convex nonlinear programming does not guarantee that a local optimum will also be a global optimum. Manne and Barreto (2001) suggest applying several different commercial solvers for large-scale nonlinear programming (NLP) models (like CONOPT2, MINOS5 or BARON) and several different starting solutions for each of them in order to check for local optima. Another approach is the development of global non-smooth (stochastic) optimization techniques (Gritsevskyi and Nakićenović, 2000).

8.5.2 Technological Change in Economic Models of Environmental Policy

Most top-down models rely on exogenous technological change. They usually incorporate an AEEI parameter and allow for backstop technologies. Typical CGE models are GEM-E3, GREEN, and MIT-EPPA. The General Equilibrium Model for Energy-Economics-Environment (GEM-E3) is a computable general equilibrium model for the European Union member states that links the macro-economy with details of the interaction with the environment and the energy system (Capros et al., 1997). Technological change in GEM-E3 is characterized by a constant AEEI parameter. The same is true for the OECD GREEN model, which assumes an AEEI parameter of 1 percent (Burniaux et al., 1992). In addition, the GREEN model has a so-called putty/semiputty dynamic structure. Two kinds of capital goods coexist in each period: capital installed in previous periods, and new capital as a result of investment in the current period. To include endogenous technological change, a vintage re-calibration is applied at the beginning of each period and parameters of the production structure are modified to reflect the changing composition of capital (Beghin et al., 1995). Substitution between energy and labor is more feasible in the most recent vintages. Hence, increased capital adjustment or replacement rates increase technological progress since energy can be better substituted by other inputs (Burniaux et al., 1992). The RICE integrated assessment model for climate change policy analysis (Nordhaus, 1994) assumes an exponential slowdown in productivity growth rate g for each region j over time (t):

$$g_j(t) = g_j(0) \cdot e^{-d_j \cdot t}, \tag{8.16}$$

where d is its constant rate of decline calibrated to historical growth rates of output per capita. Carbon-saving technological change is introduced with the assumption that decarbonization (decline in the global carbon-emissions-to-output ratio) is about 1 percent until 2005 and reduces to zero over subsequent decades (Nordhaus and Boyer, 1999). The MIT-EPPA model considers a reference AEEI parameter of 0.75 percent and backstop technologies for oil, gas and electricity. The oil and gas technologies are hydrocarbon-based, representing coal gasification and shale oil. The electricity technology is a carbon-free renewable alternative representing a combination of solar, wind, and other technologies. There is a mark-up above the base-year cost of the substituted commercial fuel for the backstop technologies. For example, the markup for sinful oil in the USA is 2.8, i.e. ceteris paribus the shale backstop technology becomes a competitive energy supply technology after a 2.8-fold increase in oil prices.

In the macroeconometric energy-environment-economy model for Europe (E3ME), induced technological change is modeled using Kaldor's technical progress function. E3ME is an econometric input-output model with 32 sectors and 14 EU regions (Barker and Köhler, 1998). The main endogenous variables in E3ME, e. g. technological change, are determined from functions estimated on historical data for European energy use and the economy. Carraro and Galeotti (1996, 1997) include induced technical change in the WARM model using again a latent variable approach with respect to the capital stock. WARM is an econometric general equilibrium model estimated for 12 EU countries. In WARM, an increase in a firm's R&D expenditure, which depends inter alia on policy variables such as environmental taxation and innovation subsidies, leads to more environment-friendly capital. The factor price bias of Jorgenson and Wilcoxen (1990) is included in DGEM.

Bottom-up models are almost exclusively technology snapshot models that examine a suite of technological alternatives over time. A number of bottom-up models have integrated endogenous technological change that assumes LBD. Examples are ETA (Kypreos, 2000), MESSAGE (Messner, 1997; Messner and Schrattenholzer, 1998; Seebregts et al., 1999; Gritsevskyi and Nakićenović, 2000) and market allocation, called MARKAL (Mattsson and Wene, 1997; Kypreos and Barreto, 1998; Barreto and Kypreos, 1999; Seebregts et al. 2000). MESSAGE, MARKAL and ETA are dynamic linear programming models of the energy sector (bottom-up), that are generally used in a tandem with the MACRO (top-down) macro-economic model which provides economic data for the energy system (Manne 1981). They optimize a choice between different technologies using given abatement costs and carbon emission targets. Both models account for the substantial uncertainty associated with the time of arrival and performance of new technologies by employing a stochastic rather than a deterministic optimization technique. Cost and performance information of a variety of advanced renewable and fossil-fuel-based alternative energy technologies are put into the model (technology snapshots). However, there is no modeling of technological change, just adoption of different available technologies. MARKAL considers 13, MESSAGE 77 technologies. Both include six learning technologies. Learning technologies in MESSAGE and MARKAL are displayed in Table 8.2. POLES adds other features of the innovation process. The share of technical potential that is realized as economic potential for a technology is described by a logistic curve and depends on the payback period. The payback period also influences the coefficient describing the speed of diffusion in a logistic diffusion curve (Kouvaritakis et al., 2000).

Table 8.2 Learning rates in MARKAL and MESSAGE (in %)

Energy technology	MARKAL	MESSAGE
Advanced coal	6	7
Natural gas combined cycle	11	15
New nuclear	4	7
Fuel cell	13	-
Wind power	11	15
Solar PV	19	18
Solar thermal	-	15

* Seebregts et al. (1999).

Endogenous learning curves are implemented in MESSAGE and MARKAL using Mixed Integer Programming (MIP) (Messner, 1997). Kypreos (2000) shows how learning can be introduced in the general equilibrium framework of ETA-MACRO. As described above, the optimization problem becomes non-linear and non-convex with technology learning and can not be solved by commercial solvers for NLP models. Therefore, the problem is linearized using the MIP formulation with a piece-wise interpolation of the cumulative cost curve. A optimal solution can be found using the sequential joint maximization algorithm by Rutherford (1999b). Manne and Barreto (2001) show for the MERGE model that standard algorithms produce plausible solutions, but further efforts are necessary to ensure a global rather than a local optimum.

Dowlatabadi and Oravetz (1997) implemented the PIEEI relationship in the Integrated Climate Assessment Model (ICAM 3). ICAM 3 is a non-optimizing, sequential, stochastic decision model with a fairly complex structure. Endogenous technological change (T_t) in ICAM is written as:

$$T_t = A(y) + E\left[\alpha \cdot \frac{p_t - p_{t-1}}{p_{t-1}}\right], \tag{8.17}$$

where A is the base energy efficiency as a function of per capita income y, α is a constant coefficient and p_t is the average price of energy. Expectations of energy price increases lead to technological innovation and diffusion. The autonomous energy efficiency parameter A accounts for the historical fact that energy intensity has dropped in most sectors even under falling energy prices. Dowlatabadi (1998) added LBD and included endogenous technological progress not only for energy efficiency in conversion and end-uses, but also in the discovery and recovery of oil and gas. The integrated model to assess the greenhouse effect (IMAGE) also uses AEEI and PIEEI to endogenize technological change. In IMAGE, the AEEI parameter is assumed to decline exponentially and is linked to the capital turnover rate (Alcamo et al., 1998). Nordhaus (1999) incorporates induced innovation as a function of the R&D-based knowledge stock and spillover effects in the R&DICE model. The model then determines carbon taxes, capital investment and the level of R&D in the energy/carbon sector that maximizes discounted per-capita consumption. FUND, another IAM, deals with technological development through running different scenarios about technological progress (Tol, 1999). Table 8.3 summarizes the treatment of technical change in well-known climate change models.

Table 8.3 Technical change characteristics in energy-economy models

Model	Type[*]	Representation of TC[**]	Reference
DGEM	CGE	Factor price bias	Jorgenson and Wilcoxen (1990)
DICE/RICE	IAM	AEEI	Nordhaus (1994)
E3ME	ME	Latent variable (Investment)	Barker and Köhler (1998)
ETC-RICE	IAM	R&D, Spillovers	Buonanno et al. (2001)
FUND	IAM	TS, Scenarios	Tol (1999)
GEM-E3	CGE	AEEI	Capros et al. (1997)
GOULDER	ME	LBD, R&D, Spillovers	Goulder and Mathai (2000)
	CGE	R&D, Spillovers	Goulder and Schneider (1999)
GREEN	CGE	AEEI, Vintages	Burniaux et al. (1992)
ICAM3	IAM	LBD, PIEEI, TS	Dowlabadi (1998)
IMAGE	IAM	AEEI, PIEEI	Alcamo et al. (1998)
MARKAL	ES	LBD, TS	Barreto and Kypreos (1999)
MESSAGE	ES	LBD, TS	Grübler and Messner (1998)
MIT-EPPA	CGE	AEEI, Backstops	Babiker et al. (2001)
POLES	ES	LBD, Diffusion curves	Kouvaritakis et al. (2000)
R&DICE	IAM	R&D, Spillovers	Nordhaus (1999)
WARM	ME	Latent variable (Capital stock)	Carraro and Galeotti (1997)

[*] CGE: computational general equilibrium model, ES: energy system model, IAM: integrated assessment model, ME: macroeconometric model

[**] AEEI: autonomous energy efficiency improvements, LBD: learning-by-doing, PIEEI: price induced energy efficiency improvements, TS: technology snapshot

8.6 Implications of Exogenous and Endogenous Technical Change

8.6.1 Costs of Environmental Policy

The omission of induced technological change may lead to an overestimation of abatement costs and the trend increase in emissions. Price-induced technical change as studied by Dowlatabadi and Oravetz (1997) spurs technical progress as energy prices increase. This leads to a decline in energy use and carbon emissions per unit of energy, thereby lowering emissions and substantially reducing the associated costs of mitigation. Dowlatabadi (1998) added LBD, which further reduces abatement costs. Carbon taxes may lead to a change to low carbon technologies from the given menu of alternative technologies, which in turn may speed up the diffusion and bring down the costs of the new energy technologies (Azar and Dowlatabadi, 1999). However, if technological progress reduces the cost of energy consumption, endogenous technical change increases business-as-usual emissions. Therefore, additional abatement efforts are required to meet some specified target, but the associated costs will also be lower (Dowlatabadi, 1998). Quantitative results from bottom-up models with relatively cheap low- or non-carbon technologies and LBD indicate low gross costs of abatement. Long-run stabilization of emissions may – without accounting for transaction costs – even be achieved at no (or negative) cost (Anderson et al., 2000).

Goulder and Schneider (1999) show that any given environmental policy target can be achieved at lower costs with induced technological change. However, lower marginal abatement costs make a greater level of abatement socially optimal. Hence, the total abatement cost in the social optimum increases with induced technological change, even though marginal abatement cost declines. Goulder and Mathai (2000) find similarly that costs and the required carbon tax are generally lower with the existence of induced technological progress than without, although the impacts of induced technical change are rather weak. In their dynamic setting, they find a lower time-profile for an optimal environmental tax with induced technological change. Even though the optimal level of abatement is higher with ITC, it can be achieved with a lower environmental tax rate. Overall, the effect of induced technological change on environmental targets seems ambiguous. The reasons for this are the uncertainties with respect to crucial innovation parameters and the R&D market failures which make environmental policy with induced technological change a ‘second best’ problem.[74]

8.6.2 Opportunity Costs of R&D Investment

Bottom-up models do not consider general equilibrium effects of induced innovation on innovation elsewhere in the economy. Models that take into account these opportunity costs of investment in R&D like those by Goulder and Schneider (1999), Nordhaus (1999) and Buonanno et al. (2001) find only weak impacts of induced technological change on the gross costs of abatement. Goulder and Schneider (1999) claim that the opportunity cost of redirecting limited R&D resources to the energy sector steepens the decline in GDP associated with the introduction of a carbon tax under induced technological change, i.e. a given tax leads to larger gross costs (25 percent higher GDP loss). The reason for this is that in equilibrium, the rate of return on R&D is equalized across sectors and equals the rate of return to other investments. An increase in R&D expenses on renewables with induced technological change leads to reduced R&D and, hence, reduced productivity in other sectors given inelastic supply of R&D inputs. Technical expertise (human capital) is ‘crowded out’ from other applications, and the gross costs for a given carbon tax rise.

In the same vein, Nordhaus (1999) finds that the opportunity cost of R&D (and LBD) is a severe limitation to the effects of induced technological change. The effects of spillovers, which provide free progress (as does LBD) and thus lessen the negative impacts of environmental policies when considered in the models (Goulder and Mathai, 2000), are also reduced by opportunity cost considerations, since high spillovers of R&D lead to high opportunity costs of redirecting R&D to the energy sector. The costliness of R&D makes the influence of induced technical change insignificant in the R&DICE model. Induced innovation (given the small share of R&D investment) seems to be a much less powerful factor in implementing climate-change policies than substitution of labor and capital for energy. Opportunity costs considerations suggest that innovation offsets may be very small.

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[74] Subsidies on industry-specific R&D lead to over-investment in R&D. However, R&D market failures (knowledge spillovers), which lead to under-investment in R&D by firms, justify R&D subsidies as a second policy instrument in addition to a carbon tax. Large spillovers, to the benefit of non-energy related industries, strengthen the argument for subsidization to overcome the R&D market failure. Carraro and Galeotti (1996, 1997) also promote a policy mix of subsidies for environmentally friendly R&D along with taxes. A counter-example, building on the crowding-out argument, is given by Kverndokk et al. (2000).

8.6.3 Timing of Abatement Measures

Grübler and Messner (1998) point out that models with an AEEI typically result in a deferral of investment decisions until the technology has become cheap enough to be competitive. Even though absolute abatement requirement increases with late action, it is still better to wait as abatement becomes cheaper. With induced technological change, the derivation of the shape of the least-cost mitigation pathway becomes more complex (Grubb, 1997). The rationale for postponed abatement is offset by the stimulus for technological development in the case of early abatement. Goulder and Mathai (2000) find that with R&D-induced technological change, some abatement is shifted from the present to the future. Induced innovation not only reduces marginal abatement costs, but also reduces the shadow cost of emissions today (because of lower future abatement costs). The optimal level of abatement is therefore lower in early years and higher later. Schneider and Goulder (1997) state the case for the early introduction of carbon taxes, but not necessarily abatement. Wigley et al. (1996) argue for postponed action. The effect of LBD-induced technological change on the time profile of abatement costs in the cost-function model of Goulder and Mathai (2000) is ambiguous. In bottom-up models with LBD, early emissions-reduction measures are preferable, since they generate knowledge that lowers the relative costs of future abatement (Grübler and Messner, 1998; Anderson, 1999). The costs of delay may be several times higher with induced technological change (adaptability) than without (Grubb et al., 1995).

8.6.4 Sensitivity of Climate Policy

Models with exogenous technological change are very sensitive to differences in assumed AEEI rates in long-term projections. Even small changes in the AEEI parameter result in large differences for energy demand and emissions in the baseline and, hence, the total costs of emissions reductions (Manne and Richels, 1990). The higher (lower) the AEEI is, the lower (higher) the baseline emissions become and the lower (higher) the costs to reach a climate target relative to a given base year are. There may be uncertainty as to the true value for the AEEI parameter. Given the multiple factors that influence changes in energy consumption over time, it is difficult to capture the appropriate value. Estimates for AEEI rates vary widely, ranging from 0.4 per cent to 1.5 per cent (Grubb et al., 1993; Manne and Richels, 1994). Assumptions about (backstop) technologies have large impacts on mitigation costs. Hourcade and Robinson (1996) showed that emissions reduction costs decrease over time, simply because more technologies become available. The magnitude of this effect depends on the characteristics of the assumed backstop technologies. The importance of technology assumptions for the costs of achieving different atmospheric concentrations is backed by Edmonds et al. (1997).

The role of (endogenous) technological change also becomes evident in long-time energy system models. The structure of energy production and the optimal technology mix implemented change considerably with technological learning. With LBD, the more widely adopted a technology is, the cheaper it becomes. Hence, it increasingly eliminates other technologies. While standard coal and nuclear power are still the dominant technologies in 2050 in the static case without LBD, advanced coal, new nuclear and solar technologies dominate the mix in the LBD case (Messner and Schrattenholzer, 1998). The penetration of renewable energy technologies leads to a stabilization of global atmospheric CO_2 concentrations at around 500 ppm (Anderson, 1999). The impact of endogenous technological change on the structure of the energy system is greatest during the near-term periods when there is a high freedom of choice across future technologies. During these periods lock-in effects and increasing returns to adoption are most important (Gritsevskyi and Nakićenović, 2000). In addition, endogenous technological change increases model uncertainties significantly. When future costs of different energy technologies are uncertain, the range of possible outcomes is extraordinary (Papatanasiou and Anderson, 2001). Potential long-term CO_2 emissions are bimodally distributed with global energy systems based either around carbon intensive or low and zero carbon resources. Due to the increasing returns to scale, the systems differ very little in terms of economic costs, yet the range of results is huge (Gritsevskyi and Nakićenović, 2000). The high sensitivity of climate policy to path-sensitivity and lock-in effects is also backed by the analyses of Grubb et al. (1995) and Ha-Duong et al. (1997).

8.6.5 International Spillovers and Leakage

In the policy debate of climate change, spillovers from Annex-B countries' abatement to non-abating developing countries play an important role. Models with exogenous technological change find negative environmental spillovers from abatement. Unilateral abatement policies will result in negative spillovers from abatement, as abatement action by one country is partly offset by increased emissions in other countries when energy intensive industries move (leakage effect). Through a more dynamic perspective, induced technological change influences the leakage effects through the international diffusion of endogenous technological progress, i.e. technology spillovers as introduced by Buonanno et al. (2001). In the presence of induced technological change, cleaner technologies developed as a response to abatement policies in industrialized countries may internationally diffuse generating positive spillovers for non-abating countries. This effect arises in ICAM (Dowlatabadi and Oravetz, 1997). The diffusion of cleaner technologies from emission constrained regions outweighs the classical components of leakage and also results in reduced emission elsewhere. The reason for this is the enormous leverage effect exerted by the diffusion of new technologies over decades (Grubb, 2000).

8.7 Conclusion

This survey presents different approaches to represent technological change and the limitations inherent in existing energy-economy-environment models. It highlights the importance of understanding the process of technological change in global climate change modeling, since the direction and extent of technological change proves crucial for the environmental impact of future economic activities. Quantifying the impacts of price-induced technological change, learning-by-doing and learning-by-using, and exogenous technological change poses a major challenge. The current state-of-the-art modeling of (endogenous) technological change still relies heavily on ad-hoc assumptions. Future extensions of the presented approaches should be targeted towards a further endogenization and an improved realism in the modeling of the process of technological change. Most important seems to be the incorporation of path-dependence and inertia, the uncertainty in major innovations, the discontinuity in the process of technological change, and the heterogeneity in firm behavior and investment incentives (Weyant and Olavson, 1999). In addition, the work of Arthur (1994) and others makes clear that endogenous specifications of technological change depend crucially on assumptions about exogenously defined parameters. This requests extended econometric studies to provide an empirical background for modeling.

Path discontinuities arise through gradual progress and major innovations. The processes of technological change are characterized by a substantial uncertainty associated with the time of arrival and performance of new technologies. It is, therefore, not possible to know what specific technologies will be successful in the future. This emphasizes the need for incorporating uncertainty in the modeling process, for example through the use of stochastic optimization techniques, the consideration of risk attitudes of decision makers and the incorporation of a very wide range of energy technologies and resources (Grübler et al., 1999; Anderson, 1999). These extensions are requisite to analyze the importance of path-dependence and inertia in long-term climate policy. The modeling of endogenous technological change may not only consider changes in technology characteristics but also in the path of technology. While other markets can often be explained by current demand and supply, markets subject to increasing returns may not be fully understandable without knowing the pattern of historical technology adoption. However, the modeling of stochastic and context-sensitive processes is limited. A first step is the explicit representation of uncertainty, a careful inclusion of LBD, time lags and assumptions about the diffusion of innovations.

Another important aspect of the innovation process not yet accounted for in energy-economy models is the heterogeneity in firm behavior and innovation incentives. Different firms respond differently to environmental policies. Additionally, new technologies are developed by an innovative firm and are not available to all firms, but diffuse over time. Heterogeneity is also addressed in a number of recent game theoretical studies related to strategic R&D investments (Ulph, 1997). It is not easy to capture these evolutionary firm level processes in a neoclassical framework. In addition, top-down models do not provide the degree of disaggregation for firm level analysis, while bottom-up models are not well suited to study strategic considerations. Given these model limitations, current applied models look at homogenous, ‘representative’ firms or industries and include spillovers and diffusion as demonstrated. The modest effects of learning-by-doing carbon abatement in aggregated models that contrast the results from bottom-up approaches may be traced back to the lack of sectoral disaggregation in top-down model approaches, which do not take into account the varying impacts of LBD on different industries at different stages of development.

Conventional energy industries tend to be mature industries, in which learning-by-doing effects may be rather small in contrast e. g. to renewable energy industries (Anderson, 1999). An interesting approach to account for heterogeneity, though not heterogeneity of firms, but more general heterogeneity of industries and technologies, is the hybrid modeling that synthesize bottom-up and top-down approaches in energy-economic models.

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