GERAD

Groupe d'études et de recherche en analyse des décisions

ENERGY AND ENVIRONMENT

Edited by

Richard Loulou

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ENERGY AND ENVIRONMENT

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Foreword

GERAD celebrates this year its 25th anniversary. The Center was created in 1980 by a small group of professors and researchers of HEC Montréal, McGill University and of the École Polytechnique de Montréal. GERAD's activities achieved sufficient scope to justify its conversion in June 1988 into a Joint Research Centre of HEC Montréal, the École Polytechnique de Montréal and McGill University. In 1996, the Université du Québec à Montréal joined these three institutions. GERAD has fifty members (professors), more than twenty research associates and post doctoral students and more than two hundreds master and Ph.D. students.

GERAD is a multi-university center and a vital forum for the development of operations research. Its mission is defined around the following four complementarily objectives:

- The original and expert contribution to all research fields in GERAD's area of expertise;
- The dissemination of research results in the best scientific outlets as well as in the society in general;
- The training of graduate students and post doctoral researchers;
- The contribution to the economic community by solving important problems and providing transferable tools.

GERAD's research thrusts and fields of expertise are as follows:

- Development of mathematical analysis tools and techniques to solve the complex problems that arise in management sciences and engineering;
- Development of algorithms to resolve such problems efficiently;
- Application of these techniques and tools to problems posed in related disciplines, such as statistics, financial engineering, game theory and artificial intelligence;
- Application of advanced tools to optimization and planning of large technical and economic systems, such as energy systems, transportation/communication networks, and production systems;
- Integration of scientific findings into software, expert systems and decision-support systems that can be used by industry.

One of the marking events of the celebrations of the 25th anniversary of GERAD is the publication of ten volumes covering most of the Center's research areas of expertise. The list follows: **Essays and Surveys in Global Optimization**, edited by C. Audet, P. Hansen and G. Savard; **Graph Theory and Combinatorial Optimization**, edited by D. Avis, A. Hertz and O. Marcotte; **Numerical Methods in Finance**, edited by H. Ben-Ameur and M. Breton; **Analysis, Control and Optimization of Complex Dynamic Systems**, edited by E.K. Boukas and R. Malhamé; **Column Generation**, edited by G. Desaulniers, J. Desrosiers and M.M. Solomon; **Statistical Modeling and Analysis for Complex Data Problems**, edited by P. Duchesne and B. Rémillard; **Performance Evaluation and Planning Methods for the Next Generation Internet**, edited by A. Girard, B. Sansò and F. Vázquez-Abad; **Dynamic Games: Theory and Applications**, edited by A. Haurie and G. Zaccour; **Logistics Systems: Design and Optimization**, edited by A. Langevin and D. Riopel; **Energy and Environment**, edited by R. Loulou, J.-P. Waaub and G. Zaccour.

I would like to express my gratitude to the Editors of the ten volumes, to the authors who accepted with great enthusiasm to submit their work and to the reviewers for their benevolent work and timely response. I would also like to thank Mrs. Nicole Paradis, Francine Benoît and Louise Letendre and Mr. André Montpetit for their excellent editing work.

The GERAD group has earned its reputation as a worldwide leader in its field. This is certainly due to the enthusiasm and motivation of GERAD's researchers and students, but also to the funding and the infrastructures available. I would like to seize the opportunity to thank the organizations that, from the beginning, believed in the potential and the value of GERAD and have supported it over the years. These are HEC Montréal, École Polytechnique de Montréal, McGill University, Université du Québec à Montréal and, of course, the Natural Sciences and Engineering Research Council of Canada (NSERC) and the Fonds québécois de la recherche sur la nature et les technologies (FQRNT).

Georges Zaccour
Director of GERAD

Avant-propos

Le Groupe d'études et de recherche en analyse des décisions (GERAD) fête cette année son vingt-cinquième anniversaire. Fondé en 1980 par une poignée de professeurs et chercheurs de HEC Montréal engagés dans des recherches en équipe avec des collègues de l'Université McGill et de l'École Polytechnique de Montréal, le Centre comporte maintenant une cinquantaine de membres, plus d'une vingtaine de professionnels de recherche et stagiaires post-doctoraux et plus de 200 étudiants des cycles supérieurs. Les activités du GERAD ont pris suffisamment d'ampleur pour justifier en juin 1988 sa transformation en un Centre de recherche conjoint de HEC Montréal, de l'École Polytechnique de Montréal et de l'Université McGill. En 1996, l'Université du Québec à Montréal s'est jointe à ces institutions pour parrainer le GERAD.

Le GERAD est un regroupement de chercheurs autour de la discipline de la recherche opérationnelle. Sa mission s'articule autour des objectifs complémentaires suivants :

- la contribution originale et experte dans tous les axes de recherche de ses champs de compétence ;
- la diffusion des résultats dans les plus grandes revues du domaine ainsi qu'auprès des différents publics qui forment l'environnement du Centre ;
- la formation d'étudiants des cycles supérieurs et de stagiaires post-doctoraux ;
- la contribution à la communauté économique à travers la résolution de problèmes et le développement de coffres d'outils transférables.

Les principaux axes de recherche du GERAD, en allant du plus théorique au plus appliqué, sont les suivants :

- le développement d'outils et de techniques d'analyse mathématiques de la recherche opérationnelle pour la résolution de problèmes complexes qui se posent dans les sciences de la gestion et du génie ;
- la confection d'algorithmes permettant la résolution efficace de ces problèmes ;
- l'application de ces outils à des problèmes posés dans des disciplines connexes à la recherche opérationnelle telles que la statistique, l'ingénierie financière, la théorie des jeux et l'intelligence artificielle ;
- l'application de ces outils à l'optimisation et à la planification de grands systèmes technico-économiques comme les systèmes énergétiques, les réseaux de télécommunication et de transport, la logistique et la distributique dans les industries manufacturières et de service ;

- l'intégration des résultats scientifiques dans des logiciels, des systèmes experts et dans des systèmes d'aide à la décision transférables à l'industrie.

Le fait marquant des célébrations du 25^{e} du GERAD est la publication de dix volumes couvrant les champs d'expertise du Centre. La liste suit : **Essays and Surveys in Global Optimization**, édité par C. Audet, P. Hansen et G. Savard ; **Graph Theory and Combinatorial Optimization**, édité par D. Avis, A. Hertz et O. Marcotte ; **Numerical Methods in Finance**, édité par H. Ben-Ameur et M. Breton ; **Analysis, Control and Optimization of Complex Dynamic Systems**, édité par E.K. Boukas et R. Malhamé ; **Column Generation**, édité par G. Desaulniers, J. Desrosiers et M.M. Solomon ; **Statistical Modeling and Analysis for Complex Data Problems**, édité par P. Duchesne et B. Rémillard ; **Performance Evaluation and Planning Methods for the Next Generation Internet**, édité par A. Girard, B. Sansò et F. Vázquez-Abad ; **Dynamic Games : Theory and Applications**, édité par A. Haurie et G. Zaccour ; **Logistics Systems : Design and Optimization**, édité par A. Langevin et D. Riopel ; **Energy and Environment**, édité par R. Loulou, J.-P. Waaub et G. Zaccour.

Je voudrais remercier très sincèrement les éditeurs de ces volumes, les nombreux auteurs qui ont très volontiers répondu à l'invitation des éditeurs à soumettre leurs travaux, et les évaluateurs pour leur bénévolat et ponctualité. Je voudrais aussi remercier Mmes Nicole Paradis, Francine Benoît et Louise Letendre ainsi que M. André Montpetit pour leur travail expert d'édition.

La place de premier plan qu'occupe le GERAD sur l'échiquier mondial est certes due à la passion qui anime ses chercheurs et ses étudiants, mais aussi au financement et à l'infrastructure disponibles. Je voudrais profiter de cette occasion pour remercier les organisations qui ont cru dès le départ au potentiel et la valeur du GERAD et nous ont soutenus durant ces années. Il s'agit de HEC Montréal, l'École Polytechnique de Montréal, l'Université McGill, l'Université du Québec à Montréal et, bien sûr, le Conseil de recherche en sciences naturelles et en génie du Canada (CRSNG) et le Fonds québécois de la recherche sur la nature et les technologies (FQRNT).

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Preface

This volume on energy and environmental modeling describes a broad variety of modeling methodologies, embodied in models of varying scopes and philosophies, ranging from top-down integrated assessment models to bottom-up partial equilibrium models, to hybrid models. Other articles call upon multicriteria and differential games methodologies.

In Chapter 1, F. Cabo, G. Martín-Herrán and M.P. Martínez-García analyze the existence of a sustained growth in two regions connected by trade. This trade flows from a resource-based economy, the South, to a developed country, the North. The natural resource intensive good produced in the South is used as a input in the North which produces a final consumption good. Investment in this latter is devoted either to increase the capital stock in the final output sector or to improve the productivity of the resource-based input in an environmental R&D sector. A differential game between these two regions allows us to determine endogenously the price of the traded good. The balanced growth paths that ensure a permanent growth of consumption in both regions not exhausting natural resources are characterized. The transition period towards these balanced paths is also presented.

In Chapter 2, L. Drouet, A. Haurie, M. Labriet, P. Thalmann, M. Vielle, and L. Viguier report on the coordinated development of a regional module within a world computable general equilibrium model (CGEM) and of a bottom-up energy-technology-environment model (ETEM) describing long term economic and technology choices for Switzerland to mitigate GHG emissions in accordance with Kyoto and post-Kyoto possible targets. The chapter discusses different possible approaches for coupling the two types of models, and describes a scenario built from a combined model where the residential sector is described by the bottom-up model and the rest of the economy by the CGEM. Results are presented and commented.

In Chapter 3, J. Geldermann, M. Treitz, V. Bertsch and O. Rentz present the contribution to the RODOS system of a multicriteria and multi-stakeholder decision analysis model based on the tool Web-HIPRE in ensuring the transparency of decision processes within off-site emergency management. The real-time on-line RODOS decision support system helps manage conflicting objectives related to a nuclear or radiological accident in Europe. Special attention is paid to the evaluation of long term countermeasures. The RODOS modular structure and client server functionality are well suited for integrating this alternative evaluation model involving judgments and preferences. Web-HIPRE offers both MAVT and AHP elicitation methods for decision support with multiple stakeholders. A case study consisting of a hypothetical accident scenario illustrates the benefits from the model. Sensitivity analyses are also performed.

In Chapter 4, by M. Jaccard, the premise is that energy-economy models are especially useful to policy makers if they indicate the effect of energy and environment policies on the technology choices of businesses and consumers - what is called endogenous modeling of technological change. The CIMS hybrid model described in this chapter is technologically explicit, like a bottom-up engineering model, but also behaviorally realistic, like a top-down macro-economic model. With this combination, it can simulate packages of policies that include economy-wide emissions charges and technology-specific regulations and subsidies. Recent improvement to the model involves estimation of its behavioral parameters from discrete choice surveys of business and consumer technology preferences.

In Chapter 5, A. Kanudia, M. Labriet, R. Loulou, K. Vaillancourt, and J.-Ph. Waaub present the new multiregional global MARKAL-TIMES model and several recent applications to global energy-environment issues. The development of the model was motivated by the need to analyze international energy and environmental issues such as climate change, using a detailed, technology rich modeling framework. Three applications are described. First, the model is applied to conduct the cost-effectiveness analysis of Greenhouse Gas (GHG) emission abatement, whereby constraints on CO2 emissions are added to the base case formulation. The model then computes the cost-efficient response of the energy system to these emission targets. Another application addresses the issue of "who pays" for emission reductions (whereas the cost-effectiveness analysis addressed the "who acts" issue). More precisely, the model is used to devise and evaluate certain allocation rules for attributing initial emission rights to regions in a cap-and-trade system. The third application uses World MARKAL in a cost-benefit mode, i.e. the model is augmented with damage costs resulting from climate change, and the composite model is run without any pre-set targets on emissions or concentration using different scenarios depending on whether the regions cooperate or not when confronted to the threat of damages. This last application makes systematic use of game theoretic concepts.

In Chapter 6, P.L. Kunsh and J. Springael present a simulation technique (system dynamics, VENSIM code) that provides insights to public policy makers regarding the complex issues related to a market of tradable CO_2 permits. A dynamic model is designed to overcome limitations due to static and deterministic pollution-control models. The model aims at answering questions related to (1) the number of permits that should be fed into the market each year, and (2) the priorities to be given to abatement technologies. A deterministic dynamic permit model is first proposed. Then, the model addresses the uncertainties related to abatement technologies marginal cost curves as a function of the abatement levels. Fuzzy reasoning techniques rather than probability based risk approaches are used to reconcile (aggregate) the diverging expert opinions (credibility scoring levels) and to take into account uncertainties on marginal abatement costs. This model runs on a rather short horizon (five years) assuming regular updating of data.

In Chapter 7, A. Manne and R. Richels present the most recent incarnation of the MERGE general equilibrium model. MERGE is a model for estimating the regional and global effects of greenhouse gas reductions. It quantifies alternative ways of thinking about climate change. The model contains submodels governing: the domestic and international economy; energy-related emissions of greenhouse gases; non-energy emissions of GHGs; and global climate change - market and non-market damages. These submodels are fully integrated in a series of regional general equilibrium models, each consisting of a constrained non-linear convex optimization program. A global equilibrium is computed via an iterative sequence of optimizations of the regional models.

In Chapter 8, G. Mavrotas and D. Diakoulaki present the application of Mixed Integer Multiple Objective Linear Programming (MIMOLP) to the power generation expansion problem of Crete for the period 2005-2020. This modelling approach was motivated by the need to effectively incorporate environmental (CO_2 emissions) and social considerations in energy decisions. The model with integer variables is solved using the Multi-Criteria Branch and Bound (MCBB) method which generates all the efficient points for problems with combinatorial features. The Crete case study is described and the model is used to compute a cost-efficient configuration of the energy systems (capacity expansion) that complies with the objective of minimizing CO_2 emissions, and exploits the flexibility offered by the forthcoming emission trading mechanism. The results are synthesized by a trade-off curve between CO_2 emissions and costs over the time horizon. It shows that considerable emission reductions can be achieved at relatively low costs. Each solution corresponds to an investment plan provided by the model as other useful information for decision makers.

In Chapter 9, S. Paltsev, H. Jacoby, J. Reilly, L. Viguier, and M. Babiker study the role played by existing fuel taxes in determining the welfare effects of exempting the transportation sector from measures to control greenhouse gases. To evaluate this role, the MIT Emissions Prediction and Policy Analysis (EPPA) model was modified to disaggregate the household transportation sector. This improvement requires an extension of the GTAP data set that underlies the model. The revised and extended facility is then used to compare economic costs of cap-and-trade systems differentiated by sector, focusing on two regions: the USA where the fuel taxes are low, and Europe where the fuel taxes are high. The authors find that the interplay between carbon policies and pre-existing taxes leads to different results in these regions: in the USA exemption of transport from such a system would increase the welfare cost of achieving a national emissions target, while in Europe such exemptions will correct pre-existing distortions and reduce the cost.

In Chapter 10, P.-O. Pineau and S. Schott study how electricity pricing and technology choices can affect greenhouse gases (GHG) emissions and capacity requirements. They use an innovative approach to model the electricity market under a time of use tariff, where they account for the cross-price elasticity of demand between peak and of peak periods. Applying their model to the Canadian province of Ontario, they show that the combined effect of time of use prices and an "allowance price" for GHG emissions could cut capacity requirements by 20% to 30%, while price increases would be moderate if nuclear technology is chosen. If natural gas or coal technologies were chosen, off-peak price would increase by at least 13% while peak price would increase by a minimum of 20%. In terms of absolute GHG emissions, a reduction compared to the 2003 situation is only possible if coal is phased out and replaced with either nuclear or natural gas power plants. The contribution of this chapter is in its integration of two critical elements required to analyze the electricity sector: (1) how tariff structures and technologies have significant impacts on demand and capacity requirements, and (2) how price and cross-price elasticities are important demand management tools.

In Chapter 11, D. Van Regemorter describes an approach to integrate the interactions between environmental targets in an energy system optimization model, MARKAL/TIMES, so as to allow for an integrated policy evaluation. The environmental problems considered are global warming and local air pollution, both linked to energy production and consumption, and their abatement possibilities are interrelated. This explains the choice of a partial equilibrium model for the energy market to study these policy questions. With the damage generated by emissions integrated in its objective function, the model allows to optimally compute trade-offs between environment protection and economic costs. The MARKAL/TIMES model and the integration of the externalities are described. The data used for the quantification and the valuation of the externalities linked to the supply and use of energy rely heavily on the ExternE EU project dedicated to the evaluation of the external cost of energy. An application with the Belgian MARKAL/TIMES model is presented.

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The Editors would like to express their gratitude to the authors for their contributions and timely responses to our comments and suggestions. We wish also to thank Francine Benoît and André Montpetit for their expert editing of the volume.

RICHARD LOULOU
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Chapter 1

NORTH–SOUTH TRADE AND THE SUSTAINABILITY OF ECONOMIC GROWTH: A MODEL WITH ENVIRONMENTAL CONSTRAINTS

Francisco Cabo
Guiomar Martín-Herrán
María Pilar Martínez-García

Abstract We present a model of trade between two different regions, North and South. The South specializes in a natural resource intensive good which is sold to and used as an input in the North. Assuming an environmental R&D sector in the North, which increases the efficiency of the traded good, the North–South trade and the natural resource management are modeled in a dynamic way. The existence of a sustained growth in the North, which allows a permanent growth of consumption in the South without exhausting natural resource, is proved. Transitional dynamics is also studied.

1. Introduction

Through the ages, countries have reached beyond their own borders to obtain raw and essential materials. Today's surer communications and increased trade have greatly enlarged this process and endowed it with far-reaching ecological implications. Thus, the pursuit of sustainability needs to take international economic relations into account. Moreover, the conservation of ecosystems on which the global economy depends must be guaranteed. International economic exchanges must also be made beneficial for all countries involved, ensuring the improvement of living conditions in poorer countries. Today, for many developing countries, neither of these conditions is met.

In this paper we present a model of trade between two different regions, North and South, and we studIIn our model, international trade is the channel through which part of the economic growth in the North is transmitted to the South. We shall prove that income can grow constantly in both countries while at the same time guaranteeing environmental conservation.

The sustainability of economic growth has been a subject of great attention in recent years. In the literature on endogenous growth several authors include environmental variables within their models in order to study economic policies that guarantee sustainable growth (Gradus and Smulders, 1993; Huang and Cai, 1994; Ligthart and van del Ploeg, 1994; Verdier, 1995; Bovenberg and Smulders, 1995, 1996; Musu, 1996; Bovenberg and Mooij, 1997, among others). However, all these models focus on an isolated country and do not consider trade relations with other countries. In fact, most of the papers on endogenous growth regarding environmental problems do not consider more than one region. Even those that consider several countries assume that all countries are identical, see, for example, Hettich (2000).

Unlike the previous works, and following Cabo, Escudero and Martín-Herrán (2002) we present a model with two different regions, North and South, that trade with each other. Within this framework of North – South trade and following the static approach laid down, for example, by Chichilnisky (1994); Panayotou (1994); Copeland and Taylor (1994, 1995), and Cabo (1999), we assume that the South specializes in a natural resource intensive good which is used as a productive input in the North. The North – South trade and the management of the environment is modeled in a dynamic way so that sustainable economic growth can be analyzed. A unique renewable resource is harvested to produce a resource intensive good. The North buys this good in the international market and uses it as an input to produce final output. Hereinafter, we will refer to this intermediate good, traded from South to North, as the resource-based input.

More ecological production technologies must be developed to sustain the current standard of living without depleting natural resources. One of the main achievements of the endogenous growth theory is to explain technological change endogenously. Romer (1990) incorporates R&D activities in an endogenous growth model. Grossman and Helpman (1991) (Chapters 3 and 4), Aghion and Howitt (1992) and Barro and Sala-i-Martin (1995) (Chapters 6, 7 and 8) are also classical references. In these models technological progress is attained by devoting resources to research activities. Technological knowledge either augments labor productivity in the final output production function, expands product variety or improves product quality. Thus, if human inventiveness has no limit the economy will grow indefinitely. In our paper, technological knowledge enhances the productivity of the resource-based input. In the literature on environment and economic growth, Bovenberg and Smulders (1995, 1996) and Musu (1996) consider a technological knowledge of this kind. Although Musu (1996) assumes that the technological progress is a by-product of capital accumulation, we, following Bovenberg and Smulders (1995, 1996), incorporate an environmental R&D sector which is devoted to increasing the efficiency of the resource-based input in the North's output production.

The engine of growth in this paper is not based uniquely on technological progress. A second source of growth stems from a learning-by-doing effect which indefinitely raises the productivity of the labor force. We follow the idea of Romer (1986) to eliminate diminishing returns to the factors, regarding knowledge as a by-product of capital accumulation. A firm that increases its physical capital learns at the same time how to produce more efficiently. Additionally, we assume that each firm's stock of knowledge is a public good which spills over instantly across all other firms and at no cost. This leads labor productivity to be dependent not on each firm's capital stock but on the whole economy's one. These two effects are taken into account in our paper to explain how labor affects the North's production function.

The model is stated as a differential game between North and South. The South possesses a natural resource and decides the extraction effort required to produce the resource-based input traded to the North. The South maximizes its discounted utility, which is an increasing function of its total income, given by the monetary value of the intermediate traded good. On the other hand, the North fixes the consumption, the demand for the resource-based input and the portion of the labor force devoted either to the final output sector or to the environmental R&D sector. This region equally maximizes its discounted utility, which is a function of its intertemporal consumption.

In this North – South trade model, we focus on the circumstances under which a balanced path follows from the optimal decisions of both players. We shall prove that along this balanced path Northern optimal choices regarding consumption, demand for the resource-based input and the labor share devoted either to the final output or to the R&D sector, guarantee the economic growth without being so demanding as to oblige the South to deplete its natural resource. Likewise, along this balanced path, the optimal extraction effort in the South is high enough to sustain economic growth but without endangering the conservation of the renewable natural resource. In consequence we refer to this balanced growth path as sustainable.

Most endogenous growth models which take into account environmental quality restrict the analysis to the steady state, which represents the sustainable growth path. In steady state, all variables grow at their long-run rates, and the use of natural resources is sustainable. However, in the real world, economies are not usually on sustainable growth paths, there might be imbalances between different sectors, or, as usually happens, the use of the natural resource might be above its sustainable level. Two aspects must be taken into account. Firstly, stability analysis will show whether there are transition paths to sustainability. Secondly, it is interesting to know how the economies behave during transitions. Martínez-García (2001, 2003) has proved that balanced paths in endogenous growth models are either unstable or possesses the saddle point property. In this paper we shall prove that this property is satisfied. Therefore, there exist transition economic policies that lead the economies to sustainability. In addition, we shall undertake a transitional dynamic analysis, which studies the dynamics of the model in the short and medium terms when it is not on the balanced path and shows losses and gains of either growth or welfare during the adaptation process.[1] This analysis has been largely ignored in the literature due to its complexity. Usually the study can be analytically carried out for the simplest models, although more complex specifications, such as our formulation, would require the implementation of numerical methods. In our paper we follow the numerical algorithm developed by Mulligan and Sala-i-Martin (1991, 1993), known as the time elimination method, which is well suited to characterizing the transitional dynamics of endogenous growth models.

The plan of this paper is as follows: in Section 2 we model the economies of two different regions and the trade relationships between them. Optimal paths in both regions as well as the equilibrium price of the traded good are studied in Section 3. We focus on the balanced path in Section 4, while transitional dynamics is analyzed in Section 5. Finally, we present our conclusions in Section 6.

2. The model

Two different regions that trade between themselves are modeled. The Northern region produces a unique final output, which can be used either to consume or to increase the stock of physical capital. The production process uses capital, labor and a resource-based input which is

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[1] For more information about the reasons to study the transitional dynamics see, for example, Hettich (2000) and Steger (2000).

produced in the South by harvesting from a renewable natural resource. We assume a learning-by-doing effect, which implies that the work force experience will have a positive effect on the labor productivity in the North. That is, when a firm invests in physical capital, at the same time its workers learn how to produce more efficiently.

In addition to the final output sector and following Bovenberg and Smulder (1995, 1996), we introduce an environmental R&D sector. This pure investment sector produces a technology that enhances the efficiency of the resource-based input in the production of final output. Thus the production function is given by:

$$Y(t) = K(t)^{\alpha}\big(h(t)R_N(t)\big)^{\beta}(K(t)v(t)\bar{L})^{1-\alpha-\beta}, \qquad \alpha, \beta, \alpha+\beta \in (0,1), \quad (1.1)$$

where $K(t)$ represents the capital stock, $R_N(t)$ the resource-based input, $\bar{L}$ the constant labor and $h(t)$ the technological knowledge or efficiency of $R_N(t)$ in the production of $Y(t)$. All variables are evaluated at time t. From the total labor, the portion $v(t) \in (0,1)$ is devoted to final output production. The remainder, $1 - v(t)$, goes to the environmental R&D sector increasing the productivity of the resource-based input according to the dynamic equation:

$$\dot{h}(t) = \eta\big(1 - v(t)\big)h(t)\bar{L}, \quad \eta > 0. \qquad (1.2)$$

The dynamics for the capital stock is given by the total production,[2] $Y(K, hR_N, Kv\bar{L})$, minus consumption, c, and the cost of the resource-based input,[3] pR_N:

$$\dot{K} = Y(K, hR_N, Kv\bar{L}) - pR_N - c, \qquad (1.3)$$

where p is the price of the resource-based input.

The North maximizes its intertemporal utility, discounted at the rate of time preference $\rho > 0$. It chooses consumption, demand for the resource-based input and the labor share devoted to the final output sector. The maximization problem is subject to the dynamics of the capital stock and the technological knowledge.

$$\max_{c, R_N, v} \int_0^{\infty} e^{-\rho t} \ln(c)\, dt,$$

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[2] Henceforth, we omit time arguments when no confusion is caused by doing so.

[3] We assume that no asset can be internationally traded. Furthermore, all firms maximize current profits, which proves that all firms behave in the same way with respect to the capital per labor unit and the resource-based input per labor unit. All these hypotheses, together with the perfect competition assumption, allow us to write expression (1.3).

$$\begin{aligned} \text{s.t. } \dot{K} &= K^{\alpha}(hR_N)^{\beta}(Kv\bar{L})^{1-\alpha-\beta} - pR_N - c, \quad K(0) = K_0, \\ \dot{h} &= \eta(1-v)h\bar{L}, \quad h(0) = h_0, \\ & c, R_N \geq 0, \quad v \in (0,1), \end{aligned}$$

where a logarithmic specification for the North's utility is assumed.

As far as the South is concerned, it harvests from a renewable natural resource. With the extracted amount it produces a resource-based input which is traded to the North and used to produce final output. The dynamics of the natural resource stock, s, is defined by a differential equation of the type described by Clark (1990). This equation equals the evolution of the resource to the natural resource growth, $F(s)$, minus the human depletion. The logistic growth function is considered to define $F(s)$. On the other hand, the rate of harvesting is proportional to the extraction effort and the stock of the natural resource:

$$\dot{s} = rs(1 - s/\mathrm{cc}) - qEs, \tag{1.4}$$

$$0 \leq s \leq \mathrm{cc}, \tag{1.5}$$

where r is the intrinsic growth rate, cc is the environmental carrying capacity or saturation level, q is a proportionality parameter and E is the extraction effort allocated to the natural resource.

The production of the resource-based input depends on the stock and the extraction effort of the natural resource:

$$R_S = \Phi(E, s) = Es^{\theta}, \tag{1.6}$$

where $\theta \in (0,1)$ and $\Phi_E, \Phi_s > 0$. A higher stock of the natural resource leads to a higher productivity of the total effort and consequently to a greater production of the resource-based input. In this formulation θ represents the elasticity of the resource-based input with respect to the stock of the natural resource, $\varepsilon_s^{R_S}$.

The South has to decide the harvesting effort, E. This region maximizes its stream of utility discounted at rate $\rho' > 0$. No investment process occurs in the South, all income is consumed and the utility equals the logarithmic transformation of this consumption, $\ln(pR_S)$.

The maximization problem for this region can be expressed as:

$$\begin{aligned} &\max_E \int_0^{\infty} e^{-\rho' t} \ln(pEs^{\theta})\, dt \\ &\text{s.t. } \dot{s} = rs(1 - s/\mathrm{cc}) - qEs, \quad s(0) = s_0, \\ &\quad E \geq 0, \quad \theta \in (0,1). \end{aligned}$$

As well as in the North, the intertemporal elasticity of the South's utility is also constant and equal to one.

In the specified North – South trade model, each region maximizes utility and takes as given the world market price of the resource-based input. This fact suggests that either both regions are myopic (unaware of the effect of their decisions upon the price of the traded good), or that each of them represents a price-taker small open economy (the North a developed country and the South a developing one).

3. North and South's optimal paths

Next we characterize optimal paths for both regions as well as the equilibrium price of the traded good. This price stems from equating South's supply and North's demand.

The current-value Hamiltonian for the North is given by,

$$H_N = \ln(c) + m_K[K^{1-\beta}(hR_N)^{\beta}(v\bar{L}^{1-\alpha-\beta} - pR_N - c] + m_h[\eta(1-v)h\bar{L}], \quad (1.7)$$

where m_K and m_h denote the shadow prices of the capital stock and the technological knowledge, respectively.

The first order conditions for an interior maximum are:

$$1/c = m_K, \quad (1.8a)$$

$$p = \beta h K^{1-\beta}(hR_N)^{\beta-1}(v\bar{L})^{1-\alpha-\beta}, \quad (1.8b)$$

$$m_h \eta h = m_K(1-\alpha-\beta)K^{1-\beta}(hR_N)^{\beta}(v\bar{L})^{-\alpha-\beta}, \quad (1.8c)$$

$$\dot{m}_K = m_K[\rho - (1-\beta)(hR_N/K)^{\beta}(v\bar{L})^{1-\alpha-\beta}], \quad (1.8d)$$

$$\dot{m}_h = m_h[\rho - \eta\beta/(1-\alpha-\beta)v\bar{L} - \eta(1-v)\bar{L}]. \quad (1.8e)$$

Equation (1.8a) says that the marginal utility of consumption should equal the shadow price of the capital stock (the marginal benefit of increasing the capital stock in one unit). The marginal productivity of the resource-based input equals its price in equation (1.8b). Condition (1.8c) states that the ratio between the marginal benefit of an additional unit of capital, m_K, and the marginal benefit of an additional unit of technological knowledge, m_h, is equal to the marginal effect on the technological growth of an extra-unit of labor in this sector divided by the marginal effect on the capital growth of an additional unit of labor in the final output sector. The necessary condition (1.8d) shows that the marginal productivity of the capital stock plus the rate of change of the marginal benefit of an additional unit of capital should equal the depreciation rate. At the same time the value of the marginal productivity of the technology plus this factor's rate of growth plus the rate of change of the marginal benefit of an additional unit of technology should also be equal to the depreciation rate. This condition corresponds to equation (1.8e).

From conditions (1.8b) and (1.8c) the optimal demand for the resource-based input and the optimal labor share in the final output sector can be written in terms of the price and the state and costate variables:

$$\begin{aligned} R_N &= \beta^{1/\alpha}[(1-\alpha-\beta)/(\eta\beta)]^{(1-\alpha-\beta)/\alpha}[m_K/m_h]^{(1-\alpha-\beta)/\alpha} \\ &\quad \times [K/h]^{(1-\beta)/\alpha}[p/h]^{-1-\beta/\alpha}, \\ v\bar{L} &= \beta^{1/\alpha}[(1-\alpha-\beta)/(\eta\beta)]^{(1-\beta)/\alpha}[m_K/m_h]^{(1-\beta)/\alpha} \\ &\quad \times [K/h]^{(1-\beta)/\alpha}[p/h]^{-\beta/\alpha}. \end{aligned} \tag{1.9}$$

The current-value Hamiltonian function for the South reads:

$$H_S = \ln(pEs^{\theta}) + m_s[rs(1 - s/\text{cc}) - qEs], \tag{1.10}$$

where m_s is the South's shadow price of the natural resource stock.

The first order conditions for an interior maximum in this region are:

$$E = 1/(qm_s s), \tag{1.11a}$$

$$\dot{m}_s = [\rho' - r(1 - 2s/\text{cc}) + qE]m_s - \theta/s. \tag{1.11b}$$

The optimal harvesting effort is negatively related to the current stock of the natural resource. However, at the same time, this effort is sensitive to the shadow price of the natural resource. Thus, the more highly the South values this stock, the lower the extraction effort.

From equation (1.6) and the optimal effort in (1.11a), the optimal supply of the resource-based input also depends negatively on m_s and s:

$$R_S = 1/(qm_s s^1 - \theta). \tag{1.12}$$

The optimal supply of the resource-based input is independent of its price, p, or equivalently, the price elasticity of the supply for the resource-based input is zero. This supply determines the amount sold to and used in the North, and pR_S matches total income in the South.

By equating South's supply in (1.12) and North's demand in (1.9), the equilibrium price for the resource-based input can be written:

$$\begin{aligned} p = \Psi[qm_s s^{1-\theta}]^{\alpha/(\alpha+\beta)}[m_K/m_h]^{(1-\alpha-\beta)/(\alpha+\beta)} \\ \times [K/h]^{(1-\beta)/(\alpha+\beta)}h, \end{aligned} \tag{1.13}$$

where constant $\Psi \equiv \beta[(1-\alpha-\beta)/\eta]^{(1-\alpha-\beta)/(\alpha+\beta)} > 0$.

The first term in brackets in (1.13) represents the negative relationship between this price and the supply of the resource-based input. The remainder stems from the demand side. Note that the higher the relative value of the capital stock with respect to the value of the technological knowledge, m_K/m_h, the lower the labor share devoted to the environmental R&D sector, and consequently the lower the growth in the resource-based input productivity. Thus, the demand for this input increases and so does its price. This is what the second term in brackets highlights. On the other hand, higher physical capital enhances the demand for the resource-based input and, consequently, its price. Finally, the effect of a higher technological knowledge is twofold. It increases the efficiency of R_N, reducing the demand for this good and, at the same time, it speeds up the growth rate of the technology accumulation. This leads to a reduction in the labor share in the R&D sector and an increment in the final output sector. Again, a higher v increases the demand for the resource-based input. The former effect reduces the price while the latter raises it. If the output elasticity of the labor factor, $1-\alpha-\beta$, is greater than the output elasticity of the resource-based factor, β, then the former effect is stronger and the price falls.

4. The balanced path

A balanced path is a trajectory where all variables grow at constant rates (which may in some cases be zero). The labor share devoted to the final output sector takes values between zero and one, while the natural resource stock has to be positive and lower than its carrying capacity. Thus, since v and s are upper and lower bounded, they cannot grow indefinitely at non-zero rate. These variables must be constant on a balanced path. On the other hand, since the production of the resource-based input depends on the extraction of the natural resource, which is bounded, this good also must remain constant on a balanced path. From now on we refer to this intermediate good as R, given that in equilibrium $R = R_S = R_N$.

First order condition (1.11b) for the South's maximization problem can be rewritten as:

$$\dot{m}_s/m_s = \rho' - \partial\dot{s}/\partial s - \theta/(s m_s).$$

Thus, from the optimal resource-based input in (1.12) and the dynamics of m_s, the growth rate of R can be deduced:

$$\begin{aligned} \dot{R}/R = -\dot{m}_s/m_s - \dot{s}/s &= -\rho' + \theta q E + \partial\dot{s}/\partial s - (1-\theta)\dot{s}/s \\ &= -\rho' + \theta F(s)/s + \partial\dot{s}/\partial s - \dot{s}/s. \end{aligned} \tag{1.14}$$

Given the logistic growth function, $F(s)$, considered for the natural resource, the natural growth rate per unit of resource, $F(s)/s$, is greater than the marginal growth rate $F'(s)$ at any point. Thus, $\dot{s}/s - \partial\dot{s}/\partial s$ is positive, and from (1.14) a necessary condition for a non-zero constant resource-based input is $\theta F(s)/s > \rho'$. This inequality states that the output elasticity with respect to the stock of the natural resource in the Southern production process, $\varepsilon_s^{Rs} = \theta$, times the natural growth rate per unit of resource, surpasses the rate of time preference. A necessary condition for this inequality is:

$$\theta r - \rho' > 0. \tag{1.15}$$

From equation (1.14) and the dynamics of s, the growth rate of the resource-based input can be rewritten as a function of the resource stock:

$$\dot{R}/R = \theta r - \rho' - (1+\theta)rs/\mathrm{cc}.$$

From this equation, the resource-based input remains unchanged when the natural resource stock takes the constant value:

$$s^* = (\theta r - \rho')\mathrm{cc}/[(1+\theta)r], \tag{1.16}$$

which is feasible under condition (1.15). Conversely, when inequality (1.15) is not fulfilled the resource-based input falls indefinitely and no steady state is possible.

Next we turn our attention to the dynamics of the relevant variables in the North: consumption, capital stock, technological knowledge and the labor share devoted either to the R&D or the final output sector. The dynamics along the balanced path of the price of the resource-based input and the North and South's shadow prices are also studied.

By manipulating the North's first order conditions (1.8a) and (1.8d), the growth rate of consumption is,

$$\dot{c}/c = (1-\beta)(hR/K)^{\beta}(v\bar{L})^{1-\alpha-\beta} - \rho.$$

As we have shown, v and R remain constant along a balanced path, thus the growth rate of consumption will also be constant if and only if h and K grow at the same rate.

Additionally, from (1.8c),

$$(1-\alpha-\beta)(Rh/K)^{\beta}(v\bar{L})^{-\alpha-\beta}/\eta = (m_h/m_K)(h/K).$$

Therefore the shadow prices of the physical capital and the technological knowledge also grow identically along the balanced path.

>From equation (1.9), and taking into account that R, m_K/m_h and K/h do not change along the balanced path, then neither does the ratio

p/h. The price of the resource-based input grows at the same rate as h and hence at the same as K.

Moreover, since

$$\dot{K}/K = (hR/K)^{\beta}(v\bar{L})^{1-\alpha-\beta} - pR/K - c/K,$$

the capital growth rate will be constant if capital stock and consumption grow at the same rate.

Let us define new variables: $\tilde{c} = c/K$ and $\tilde{p} = p/K$. Note that a balanced path in the original variables corresponds to the steady state in variables $\tilde{c}$, v, $\tilde{p}$, R and s. Dynamic equations for these variables are[4]:

$$\dot{\tilde{c}} = \tilde{c}[\tilde{c} - \rho], \tag{1.17a}$$

$$\begin{aligned}\dot{v} = v[&\beta\{\theta r - \rho' - (1+\theta)rs/\mathrm{cc}\} + \beta\eta + (\beta - 1)\tilde{p}R + (\beta - 1)\tilde{c}]/(\alpha + \beta) \\ &+ \beta\eta v^2/(1 - \alpha - \beta),\end{aligned} \tag{1.17b}$$

$$\begin{aligned}\dot{\tilde{p}} = \tilde{p}/(\alpha + \beta)[&-\alpha\{\theta r - \rho' - (1+\theta)rs/\mathrm{cc}\} + \beta\eta \\ &+ (\beta - 1)\tilde{p}R - (1 - \alpha - 2\beta)\tilde{c}],\end{aligned} \tag{1.17c}$$

$$\dot{R} = R[\theta r - \rho' - (1+\theta)rs/\mathrm{cc}], \tag{1.17d}$$

$$\dot{s} = rs(1 - s/\mathrm{cc}) - qRs^{1-\theta}. \tag{1.17e}$$

The equilibria for these five equations correspond to sustained growth paths. It is easy to show that there exists a unique balanced path with a constant and positive stock of the natural resource given by (1.16), as long as condition (1.15) is satisfied.

On the balanced path,[5]

$$\frac{\dot{m}_K^*}{m_K^*} + \frac{\dot{K}^*}{K^*} = \frac{\dot{m}_h^*}{m_h^*} + \frac{\dot{h}^*}{h^*} = \rho - \frac{\eta\beta}{1 - \alpha - \beta}v^* < \rho,$$

and therefore, transversality conditions, given by

$$\lim_{t\to+\infty} e^{-\rho t} m_K^*(t)K^*(t) = 0, \quad \lim_{t\to+\infty} e^{-\rho t} m_h^*(t)h^*(t) = 0, \tag{1.18}$$

are satisfied. On the other hand, since m_s and s remain constant on the balanced path, transversality condition

$$\lim_{t\to+\infty} e^{-\rho' t} m_s^*(t)s^*(t) = 0, \tag{1.19}$$

is also satisfied.

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[4] For simplicity, from now on we assume $\bar{L}$ equal to one.

[5] The star represents a variable on the balanced path.

Since the current-value Hamiltonians H_N and H_S, given by (1.7) and (1.10), are concave in state and control variables, necessary conditions for optimality, together with the transversality conditions (1.18)) and (1.19), are also sufficient conditions for optimality. Moreover, given initial conditions for state variables, if we find a path converging toward the balanced path we have found an optimal solution.

4.1 Dynamics of the natural resource

As previously stated, a sustained growth path in the North involves the use of a constant amount of resource-based input. The same is true for the stock of the natural resource. Furthermore, by (1.12) the resource-based input and the natural resource stock remain motionless if and only if the shadow value of the natural resource is also constant.

First of all we analyze the dynamic system which displays the dynamics of the resource stock and its shadow value. The former is given by (1.4) and the latter by the first order conditions in (1.11b). From the optimal extraction effort in (1.11a), the system can be written as,

$$\dot{s} = rs(1 - s/\mathrm{cc}) - 1/m_s, \tag{1.20a}$$

$$\dot{m}_s = m_s[\rho' - r(1 - 2s/\mathrm{cc})] + (1 - \theta)/s. \tag{1.20b}$$

The balanced path that guarantees a sustained economic growth is associated with constant values of s and hence m_s. Therefore, it is interesting to analyze the stability of the steady state for the system in (1.20a) and (1.20b). The steady state for the natural resource coincides with s^* in (1.16), which ensures a constant resource-based input. Additionally, the steady state for the shadow price takes the value,

$$m_s^* = (1 + \theta)^2 r/[(\theta r - \rho')(r + \rho')\mathrm{cc}] = (1 + \theta)/[(r + \rho')s^*].$$

Under condition (1.15), which ensures a positive natural resource stock, the shadow price is also positive in steady state. Under this condition, the steady state shows a saddle point stability (property proved in the first Appendix).

At this point it is interesting to ascertain the dynamic relationship between the extraction effort and the resource stock. From (1.11a) and the differential equations (1.20a) and (1.20b) it is easy to derive the dynamics of the extraction effort,

$$\dot{E} = E[q\theta E - \rho' - rs/\mathrm{cc}]. \tag{1.21}$$

The s-E phase plane in Figure 1.1, presents the unique interior steady state equilibrium, point A. If the initial condition is such that the resource stock is below its steady state value, s^*, then equilibrium A can

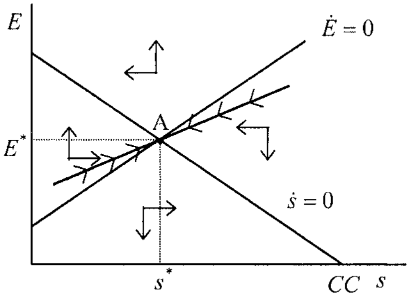

Figure 1.1. s-E phase plane

be reached as long as the South fixes a sufficiently low extraction effort, below the steady state equilibrium effort E^*. However, if this effort is too low, the system would diverge from the equilibrium to solutions with no extraction effort. Conversely, if the effort is too high, resource would fall while the effort would grow with no limit. Reverse reasoning applies when the natural resource stock is initially above s^*.

5. Transitional dynamics to sustainability

We would like to know whether a transition path to the sustainable growth solution exists. Moreover, along the transition period, growth rates of the relevant variables as well as the stock of the natural resource might not match their steady state values. Knowing how the model behaves in these transition periods is of great interest.

In our model, deviations of variable v from its steady state value represent imbalances between the final output and the innovation sectors, variable $\tilde{p}$ measures imbalances in the price of the resource-based input, while variables R and s say if the exploitation of the natural resource is above or below its sustainable level. Initially, these variables might not be at their steady state values. The stability analysis in Section 5.1 studies the existence of transition paths converging on the steady state. In Section 5.2 we analyze transitional dynamics along these paths using numerical simulation and the time elimination method of Mulligan and Sala-i-Martin (1991, 1993).

5.1 Stability analysis

The five eigenvalues of the Jacobian matrix of system (1.17) evaluated on the unique balanced path with a constant stock of the natural resource s^*, are:

$$\tilde{c}, \quad \frac{\beta\eta v^*}{1-\alpha-\beta}, \quad \frac{(\beta-1)\tilde{p}R^*}{\alpha+\beta}$$

and

$$\frac{\Omega \mathrm{cc} \pm \sqrt{\Omega^2 cc^2 + 4(1+\theta)R^* qr(s^*)^{1-\theta}\mathrm{cc}}}{2\mathrm{cc}},$$

where $\Omega = r(1 - 2s^*/\mathrm{cc}) - q(1-\theta)R(s^*)^{-\theta}$, and the star means that variables have been evaluated at their steady state values. Since the second term in the square root is positive and β is lower than 1, there are two real negative eigenvalues. Thus, the steady state is a saddle point with a two-dimensional stable manifold. Therefore, given initial conditions for the state variables, some of the imbalances in the relevant variables can be corrected to catch up with the balanced path. Because of the saddle point property these trajectories will be optimal.

Next subsection, using numerical simulation, studies which optimal policies direct the economies to the balanced path and how the growth rates behave throughout the transition periods.

5.2 Transition paths

Figures presented in this subsection display the transitional dynamics to the balanced path using the time elimination method of Mulligan and Sala-i-Martin (1991, 1993). These authors apply this method to an endogenous growth model with two-sectors, where the Jacobian matrix of the dynamic system describing the motion of the relevant variables has only one negative eigenvalue. As we have previously shown, our model presents two real negative eigenvalues and, in consequence, this algorithm has to be adapted. The methodology used is explained in the second Appendix.

For the numerical simulations the following parameters values are assumed: $\rho = 0.08$, $\rho' = 0.1$, $\alpha = \beta = 0.25$, $\eta = 0.2$, $r = 0.4$, $\mathrm{cc} = 1$, $q = 10$, $\theta = 0.5$. The temporal discount rate is higher in the South than in the North (the South discounts the future to a higher extent, $\rho' > \rho$). Concern for future generations is weaker in the South. Parameters α and β measure the elasticity of the physical capital and the resource-based input in the production of final output. Thus, returns to these two factors are equivalent to returns to labor (where the learning-by-doing process has been considered). For these parameters, a long-run growth rate of 0.04 is obtained for the North. This region invests in capital accumulation whereas in the South, which does not accumulate capital, consumption grows at this same rate along the balanced path.

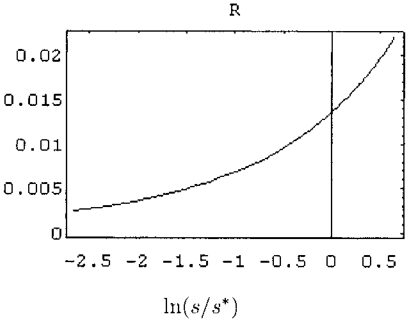

Figure 1.2. Natural resource stock

Other long-run values are $\tilde{c}^* = 0.08$, $v^* = 0.8$, $\tilde{p}^* = 2.93$, $R^* = 0.013$, $s^* = 0.16$, and $\tilde{h}^* = 0.075$.[6]

The system of nonlinear differential equations in variables R and s given by (1.17d) – (1.17e) can be numerically solved, without taking into account the rest of variables. The solution is shown in Figure 1.2, where the horizontal axis represents the deviation of variable s from its steady state level. The vertical line at zero corresponds to the steady state. If the natural resource stock is below its long-run value, i.e, if the Southern region overexploits its natural resource, an optimal policy would limit exports of the resource-based input, which has to be below its long-run value. This measure will stimulate the growth rate of s. Throughout transition, while s grows, so does R. In contrast, if the initial level of s is above s^*, an optimal policy which allows the South to catch up with its optimal level of welfare should intensify the exploitation of the natural resource.

Figure 1.3 shows the evolution of the growth rate of the resource-based input $(\dot{R}/R)$ throughout transition. The assumption of a logistic natural resource growth function, $F(s)$, implies that the lower this stock the greater its growth rate (see equation (1.4)), and, the growth rate of the resource-based input. As a consequence, $\dot{R}/R$ will be a downward sloping function of s.

On the other hand, the study of transitions also shows how imbalances between technological knowledge and physical capital in the North are corrected. These imbalances are measured by $\tilde{h}$ and they can occur regardless of whether s and R are at their stationary levels. First we shall assume that s and R are balanced, that is, $s = s^*$ and $R = R^*$, while $\tilde{h}$ is below its steady state value $(\tilde{h} < \tilde{h}^*)$. This position could correspond

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[6] This is so because $\tilde{h} = \beta^{-1/\beta}\tilde{p}^{1/\beta}R^{(1-\beta)/\beta}v^{-(1-\alpha-\beta)/\beta}$.

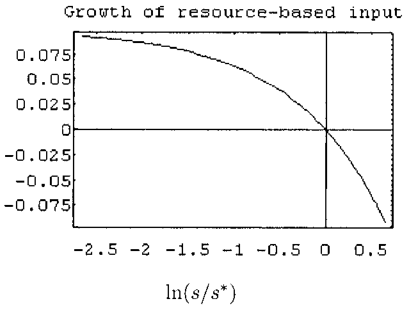

Figure 1.3. Resource-based input growth rate

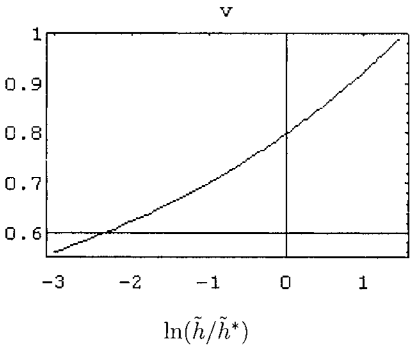

Figure 1.4. Labor devoted to production of final output

to an industrialized Northern region with high levels of capital, and production technologies intensive in resource-based input. This position is represented in Figure 1.4 by points to the left of the origin in the horizontal axis, where $\ln(\tilde{h}/\tilde{h}^*) < 0$. As this figure shows, an optimal policy will assign v below its long run value v^*, i.e, it will promote creation of knowledge and will assign more labor to the knowledge sector, at the expense of the final output sector. On the contrary, if $\tilde{h} > \tilde{h}^*$ then $v > v^*$, therefore, the knowledge sector is abandoned in favor of the final output sector. As this figure shows, the policy function v is upward sloping.

We also can see that if $\tilde{h} < \tilde{h}^*$, Northern growth rates of physical capital and consumption are lower than in the long-run (Figure 1.5) and they grow throughout transition. Moreover, these rates may even be negative when the Northern economy is too intensive in physical capital. Conversely, the growth rate of technological knowledge is higher than in the long-run (Figure 1.6 left), and decreases as the ratio between technological knowledge and physical capital balances out. Moreover,

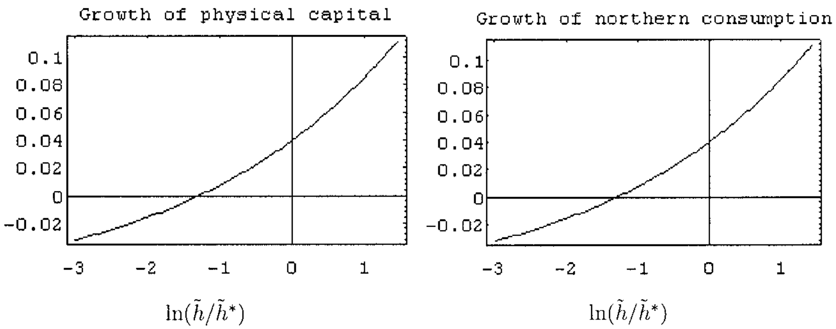

Figure 1.5. Northern growth rates of physical capital and consumption

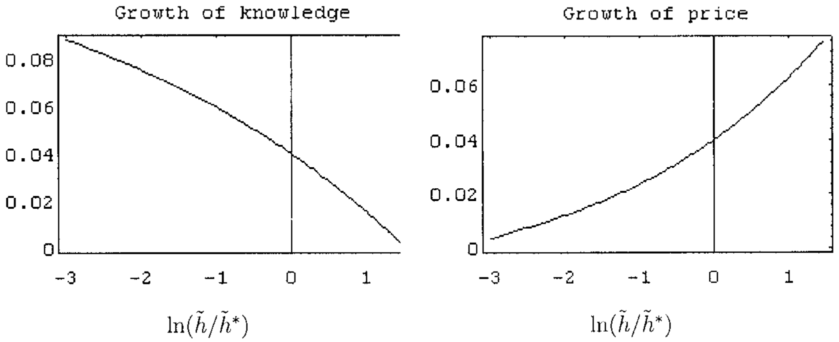

Figure 1.6. Growth rates of technological knowledge and the price of the resource-based input

the growth rate of the price of the resource-based input will be below its long-run value and will grow as $\tilde{h}$ increases (Figure 1.6 right).

It is easy to verify that, on an optimal path, South's consumption is proportional to North's final output. Indeed,

$$Y = K^{1-\beta}h^{\beta}R^{\beta}v^{1-\alpha-\beta} = \frac{1}{\beta}pR. \tag{1.22}$$

Therefore, when R is balanced, as we have been assuming up to now, the growth rates of the final output and the Southern consumption equal the growth rate of the price. All these rates increase with $\tilde{h}$ (see Figures 1.7 left and right).

However, imbalances in s and $\tilde{h}$ can simultaneously occur. Let us now assume an initial position where variable $\tilde{h}$ is below its steady state value ($\tilde{h} < \tilde{h}^*$) and the natural resource stock s is also below its long-run value. This position could correspond to an industrialized Northern region and a Southern region which overexploits its natural resource.

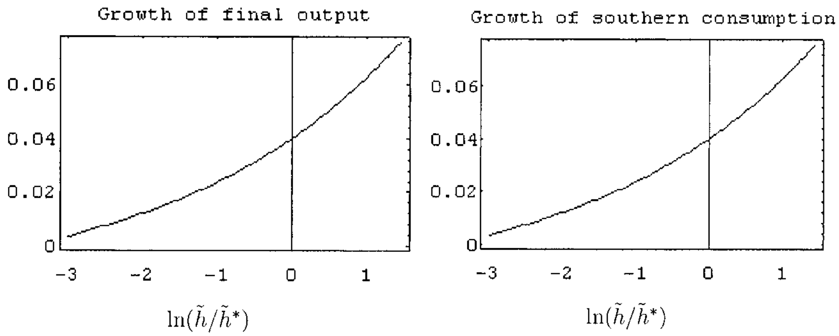

Figure 1.7. Growth rates of final output and southern consumption

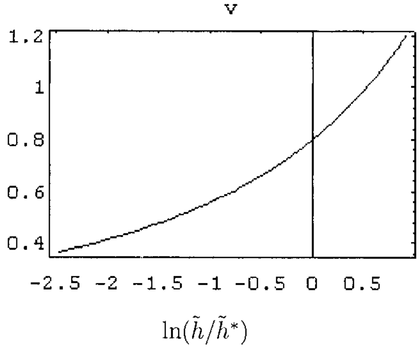

Figure 1.8. Labor devoted to the production of final output

Optimal stabilizing policies will increase the ratio $\tilde{h}$ and, at the same time, they will enhance the stock of the natural resource. These policies must promote the R&D sector — that is, $1-v$ has to be above its steady state value (see Figure 1.8) — and they must limit the use of the resource-based input, which has to be below its long-run value, as Figure 1.2 shows.

Figures 1.9 left and right show that the growth rates of Northern physical capital and consumption are, as before, lower than in the long-run, and logically, they grow along the transition path. These rates may be negative if the Northern economy is too intensive in physical capital. Conversely, the growth rate of technological knowledge is higher than in the long-run (Figure 1.10) and it diminishes as the ratio between technological knowledge and physical capital balances out.

The growth rate of the price of the resource-based input is below the long-run value (Figure 1.11). This rate could be negative if the Northern economy is too intensive in physical capital. This lower growth in prices

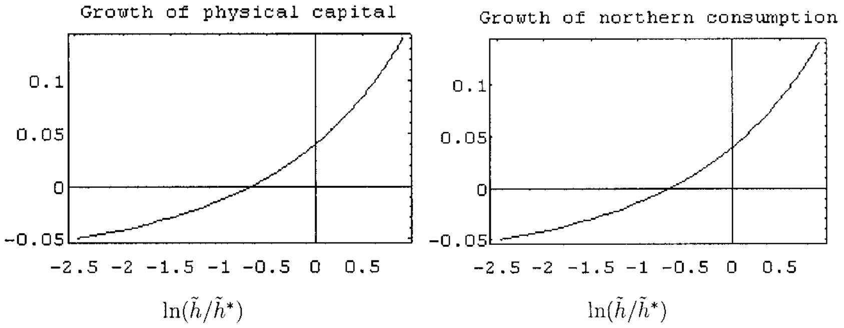

Figure 1.9. Northern growth rates of physical capital and consumption

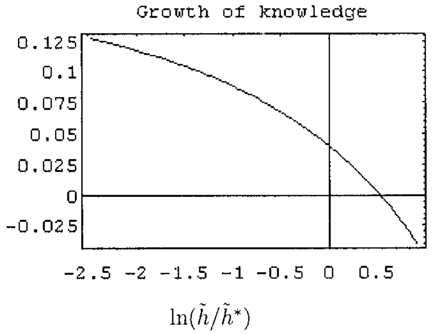

Figure 1.10. Growth rate of technological knowledge

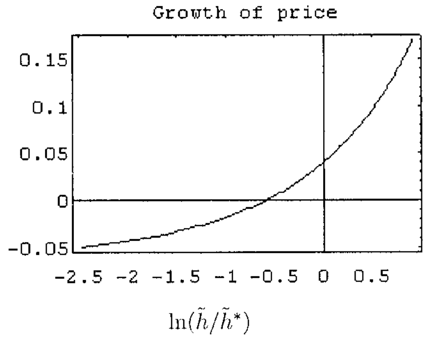

Figure 1.11. Growth rate of the price of the resource-based input

will encourage investment in the R&D sector increasing the efficiency of the resource-based input. The growth rate of its price speeds up during transition, while the growth in Southern exports slows down (see Figure 1.3).

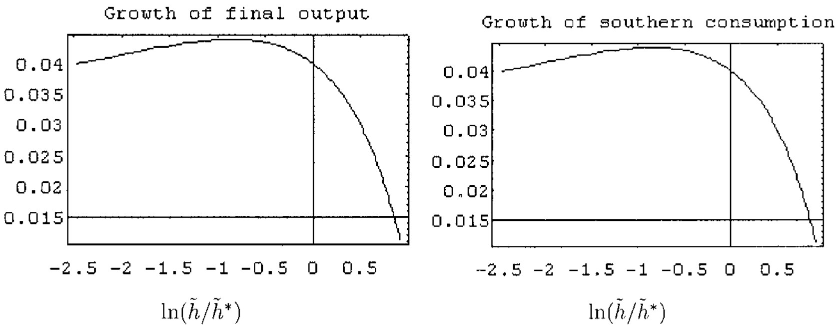

Figure 1.12. Growth rate of final output and Southern consumption

Contrary to Figures 1.7 left and right, we now obtain downward sloping curves for the growth rates of final output and Southern consumption (Figures 1.12 left and right).

The behavior of the growth rates of final output and Southern consumption will differ between different trajectories. As equation (1.22) shows, both depend on the growth rate of p, which is an increasing function of $\tilde{h}$, and the growth rate of R, which decreases with $\tilde{h}$. Thus, the behavior of the growth rates of Northern final output and Southern consumption are not determined. In some cases the growth rate of final output will be an increasing function of $\tilde{h}$ while, in others, it will be decreasing. This rejects the assertion that more environmentally friendly production technologies will always diminish the growth rate of final output. Moreover, restrictions in the use of the resource-based input will not necessarily slow down the growth rate of Southern consumption.

In the reasoning above, we have focused on trajectories which approach the origin from the left. Reciprocally, let us assume an initial position where variable $\tilde{h}$ is above its steady state value ($\tilde{h} > \tilde{h}^*$) and the natural resource stock s is also above its long-run value. This position could correspond to either a low industrialized Northern region with a low level of physical capital, or a highly developed region with a very high degree of knowledge. In both cases production technologies are less aggressive for natural resources than in the long-run. The ratio $\tilde{h} = h/k$ diminishes as s declines along an optimal path approaching the long-run solution. An optimal policy must promote the accumulation of physical capital — that is, v has to be above its steady state value (see Figures 1.4 and 1.8) — and the use of the resource-based input has to be above its long-run value, as Figure 1.2 shows. R declines throughout the transition. The growth rates of Northern physical capital and consumption are higher than in the long-run (Figures 1.5 and 1.9), and they decline during the transition. Conversely the growth rate of technological knowledge is lower than in the long-run (Figures 1.6 left and 1.10), growing as the ratio between technological knowledge and physical capital decreases. The growth rate of the resource-based input is below its equilibrium level (Figure 1.3) whereas the growth rate of its price is above the long-run value (Figures 1.6 right and 1.11). The first one increases as s declines, whereas the second one decreases as $\tilde{h}$ declines. As before, the behavior of the growth rates of final output and consumption in the South is ambiguous.

6. Conclusions

We have presented a model of regional trade between an industrialized North and a developing South. The former production process depends on capital, labor and a resource-based input imported from the South, while the latter production is based on the extraction of a natural resource. The existence of a balanced path that allows a sustained growth in the North and a permanent growth of consumption in the South, without exhausting Southern natural resources, has been proved. On a balanced path, physical capital, technological knowledge, consumption and the price of the resource-based input grow at the same constant rate. Correspondingly supply and demand for the resource-based input, as well as the stock of the natural resource, remain constant.

On the balanced path, the sustained accumulation of physical capital and technological knowledge in the North allows for a constant positive growth rate in production and consumption. Nevertheless, the wealthier North pays an increasing price for the natural resource-based input (whose productivity continuously grows). Therefore, international trade is the channel through which economic growth in the North is partially transmitted to the South. Trade revenues in the South grow constantly, as does consumption.

We have also studied transitional dynamics towards the balanced path. If there exists an imbalance between technological knowledge and physical capital in the North, being the former scarce, and the natural resource stock is below its long-run value, then optimal policies must promote the R&D sector and limit the use of the resource-based input in order to balance the ratio between technological knowledge and physical capital and to increase the stock of the natural resource. Optimal policies will also affect the growth rates of the variables.

Numerical simulations allow us to reject the idea that more environmentally friendly production technologies will invariably diminish the final output growth rate. Restrictions in the use of the resource-based input will not necessarily slow down the growth rate of Southern consumption.

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Appendix: Proof of the saddle point stability steady-state system (1.20a) – (1.20b)

The Jacobian matrix for the system (1.20a) – (1.20b) evaluated on the steady state presents two eigenvalues given by,

$$[\rho'\sqrt{1+\theta} \pm \sqrt{4r^2\theta - 4r\rho'(1-\theta) + (\theta-3)\rho'^2}]/[2\sqrt{1+\theta}].$$

These two eigenvalues display different signs if and only if,

$$\rho'^2(1+\theta) < 4r^2\theta - 4r\rho'(1-\theta) + (\theta-3)\rho'^2.$$

Last condition is equivalent to

$$r^2\theta - r\rho' + r\rho'\theta - \rho'^2 > 0,$$

and consequently to

$$(\theta r - \rho')(r + \rho') > 0.$$

Under condition (1.15) this inequality always holds and there are two real eigenvalues with different signs.

Appendix: The time elimination method

The time elimination method proposed by Mulligan and Sala-i-Martin (1991, 1993) constitutes a very simple numerical method for studying dynamic models. This method affords the advantage of transforming a boundary value problem with initial and transversality conditions into an initial value problem, where the stationary point is the appropriate boundary condition.

Since the stationary point satisfies the transversality conditions, so do all economies which lie in the stable manifold. Therefore, the stable manifold describes optimal solutions to the original optimal control problem. Given that the eigenvectors associated with negative eigenvalues are tangent to the stable manifold at the steady state, these will be used to determine the slopes of policy functions at the steady state, which is the first step in the numerical construction of a converging path.

When there exists a unique negative eigenvalue, the method can be applied with no difficulty to obtain policy functions represented by curves which depend on the unique state-like variable. This is what we have done to obtain Figures 1.2 and 1.3. Note that equations (1.17d) – (1.17e) form a system of nonlinear differential equations in variables R and s, whose Jacobian matrix, evaluated at the steady state, only presents one negative eigenvalue.

However, the whole system (1.17) has to be considered to study the dynamics of the other three variables ($\tilde{c}$, v and $\tilde{p}$). The Jacobian matrix of this system evaluated at the steady state has two negative eigenvalues, as we have shown in the second Appendix. Now, policy functions depend on two state-like variables (s and $\tilde{h}$), and they will be surfaces rather than curves. A surface is formed by an infinite number of curves and each of these curves will be a possible path that the economy could follow from some given initial values of the state-like variables to the steady state. We consider that, rather than drawing three-dimensional surfaces, it is worth taking the trouble to draw some specific curves. This procedure will be more illustrative and comprehensible on account of the structure of the Jacobian matrix.

The special structure of the Jacobian matrix allows us to ensure that the eigenvector corresponding to one of the negative eigenvalues always has zeros in positions 4 and 5. That is, when starting at the steady state, and following the direction of this eigenvector, variables s and R remain stationary. This is the vector we have used to derive Figures 1.4 to 1.7. These figures describe the motion of the optimally managed North and South economies when there are initial imbalances in $\tilde{h}$, but when s is balanced.

We are also interested in trajectories converging on the steady state which starting from a simultaneous imbalance in $\tilde{h}$ and s. The eigenvector corresponding to the other negative eigenvalue has been used to carry out this analysis, which is displayed in Figures 1.8 – 1.12. Note that taking the direction signalled by this eigenvector is equivalent to picking a single curve in the $(s, \tilde{h})$ plane, hence, policy functions are subject to this restriction. Repetition of the procedure with any different linear combinations of the two eigenvectors will produce new figures corresponding to other curves in the $(s, \tilde{h})$ plane. The motion for them all is similar to the dynamics described in Figures 1.8 to 1.12.

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Chapter 2

A COUPLED BOTTOM-UP/TOP-DOWN MODEL FOR GHG ABATEMENT SCENARIOS IN THE SWISS HOUSING SECTOR

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Maryse Labriet
Philippe Thalmann
Marc Vielle
Laurent Viguier

Abstract In this paper we report on the coordinated development of a regional module within a world computable general equilibrium model (CGEM) and of a bottom up energy-technology-environment model (ETEM) describing long term economic and technology choices for Switzerland to mitigate GHG emissions in accordance with Kyoto and post-Kyoto possible targets. We discuss different possible approaches for coupling the two types of models and we detail a scenario built from a combined model where the residential sector is described by the bottom-up model and the rest of the economy by the CGEM.

1. Introduction

This paper reports on the coordinated development of a top-down macro-economic model and a bottom-up technology-energy-environment model to assess long term climate policies in Switzerland. This work is undertaken under the aegis of a Swiss research network[1] concerned by the various dimensions of climate studies. We briefly present (i) a computable general equilibrium model (CGEM) which places Switzer-

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[1] The Swiss NSF NCCR-Climate.

land in a world model called GEMINI-E3 and (ii) a bottom-up energy-technology-environment model (ETEM) inspired from the MARKAL modelling framework. We then show how one can couple the two models to obtain a hybrid top-down/bottom-up model producing a macroeconomic scenario with detailed technology description for the residential sector in Switzerland.

In the literature the relations between the economy, the energy sector and the environment are described in two broad classes of models called *top-down* and *bottom-up* respectively. The first category approaches the problem from a description of the macro-economic relations in the region under consideration, whereas the bottom-up models propose a technology rich description of the energy system and place the emphasis on the correct description of energy options and their cost structure. These two categories of models are complementary, the former capturing a larger set of economic interactions (i.e., inter-industrial relations and macroeconomic feedbacks) without representing explicitly energy technology options and the latter representing well the details of the energy sector and the technology ranking procedures in a world characterized by technological innovation. Bottom-up models are used to compute partial economic equilibria in the energy sector under different constraints on pollutant or GHG emissions. They usually assume perfect foresight and produce optimized technology investment policies over a planning horizon of several decades typically 45 years for MARKAL models. These models are driven by energy service demands that are either exogenously defined or dependent on their own prices supposed to be indicated by the long term marginal cost of demand constraints, with exogenously defined price-elasticities. The optimization over a long time horizon coupled with a rather limited economic feedback induced by changes in relative prices makes these models more "prescriptive" than "predictive" of what could really happen.

On their side, top-down models tend to neglect the description of energy and technology options, in particular the possible introduction of new options. Because they are "technology-poor" they tend to overemphasize the economic adjustments and overlook the possible technology changes that will be induced by the changes in relative prices. Because of this complementarity it appears promising to go beyond this taxonomy of economy-energy-environment models. Already, a number of existing models are "hybrid," providing simultaneously some details on the structure of the economic and technological sectors (Böhringer, 1998; Weyant, 1999). Different approaches have been used: (i) *Coupling optimal growth models with energy system models*: ETA-MACRO and MARKAL-MACRO are examples of a coupling of a bottom-up

MARKAL model with an optimal economic growth model à la Ramsey which determines through inter-temporal optimization the optimal path of capital accumulation and demand for energy services, under specified emissions reduction (Manne and Richels, 1992; Manne and Wene, 1992). (ii) *Coupling input-output economic models with energy system models*: In this approach the economy is described by a Leontieff model of interindustry exchange; the energy sector is detailed as a linear production system. (iii) *Coupling a CGEM with an ETEM*: This is the most attractive type of coupling, since a CGEM provides a more complete representation of the different economic feedbacks and permits a correct treatment of the different taxes and market imperfections in the economy under consideration (Schafer and Jacoby, 2003).

The present paper is an attempt to implement the third type of coupling with a focus on the residential sector in the Swiss economy. The paper is organized as follows: in Section 2 we briefly recall Swiss climate policy and we show why the focus on the residential sector is justified. In Section 3 we describe the GEMINI-E3 implementation for Switzerland. In Section 4 we describe the ETEM-SWI development. In Section 5 we describe the coupling of GEMINI-E3 and the residential sector in ETEM-SWI. In Section 5.5 the scenarios obtained with the CGEM and the ETEM run in a stand-alone fashion are compared and the gain in insight obtained through the coupling is assessed. Section 6 concludes and proposes further developments.

2. Swiss CO_2 policy and the housing sector

Switzerland ratified the United Nation's Framework Convention on Climate Change (UNFCCC) in 1993 and the Kyoto Protocol in June 2003. In the Protocol, Switzerland's commitment amounts to 8% reduction in its net emissions of six greenhouse gases (GHG) over the period 2008 – 12, compared to 1990 emissions. This is the same target as for the European Union.

Switzerland does not address climate change via a single policy, but rather with a combination of measures and policies in various areas. The main spearheads of its strategy are the Federal Law on the reduction of CO_2 emissions ("CO_2 Law") and the Federal Energy Law. The 1999 CO_2 Law sets as an overall target that CO_2 emissions over the period 2008 – 12 have to be 10% below the 1990 level, with differentiated targets for heating and process fuels (−15%) and motor fuels (−8%). The law provides for a "supplementary" CO_2 tax to be implemented at the earliest in 2004 and the revenues of which are to be fully redistributed to the population and economic sectors.

The 1998 "Energy Law" calls for extensive collaboration with the private sector, mainly within the framework of a public voluntary programme called "SwissEnergy," which replaces the "Energy 2000" programme that ran from 1990 to 2000. Private energy agencies have been created in order to coordinate, evaluate and monitor voluntary initiatives. The programme mainly focuses on energy efficiency measures, in particular for electrical appliances and vehicles, but also favours the production and use of renewable energy.

This unique combination of voluntary approaches with an emissions trading programme and a CO_2 tax has been analyzed in Baranzini et al. (2004). Here we emphasize the role of housing in energy consumption, CO_2 emissions and efforts to reduce those emissions. Some background information on global energy consumption and CO_2 emissions is nevertheless necessary.

Swiss CO_2 emissions are stabilized since the 1990s, but it is doubtful that they will decline to the targets set in the Kyoto Protocol and CO_2 Law. In 2002, total GHG emissions amounted to 52.3 million tonnes of CO_2 equivalents. CO_2 represents the largest proportion of gross GHG emissions (about 84%). About 80% of total GHG emissions are energy related. Given the Swiss energy consumption profile, this means that the greatest part of GHG emissions stems from the use of fossil fuels. That explains why the CO_2 Law only addresses CO_2 emissions linked to the energetic use of fossil fuels.

Figure 2.1 shows the main CO_2 sources since 1990 (from Swiss GHG inventory in SAEFL, 2000). The shares are quite stable. Transportation accounts for the largest share, rising slowly from about 32% in the early 1990s to 35% in the early 2000s. The share of emissions from residential energy use was about 27% in the first half of the 1990s and declined to about 25% today. In total quantity those emissions were hardly lowered but per capita they went down from 1.82 tonne in 1991 to 1.52 tonne in 2002.

Note the relatively small share of industry-related CO_2 emissions. Indeed, Switzerland imports a very large proportion of intermediate and final goods with high energy content. The emissions associated with the production of those goods are not counted as Switzerland's contribution to the accumulation of GHGs. They have been estimated at 60 to 70% of domestic emissions. A second and related factor is the near absence of heavy industries and the high share of the services sector in GDP (67% in 1999). A third factor is the near absence of coal- or oil-fired power plants for electricity generation. The first nuclear power plant was hooked to the grid in 1969. Thirty years later, nuclear power plants produce nearly 35% of electric energy. 60% are produced by hydroelectric

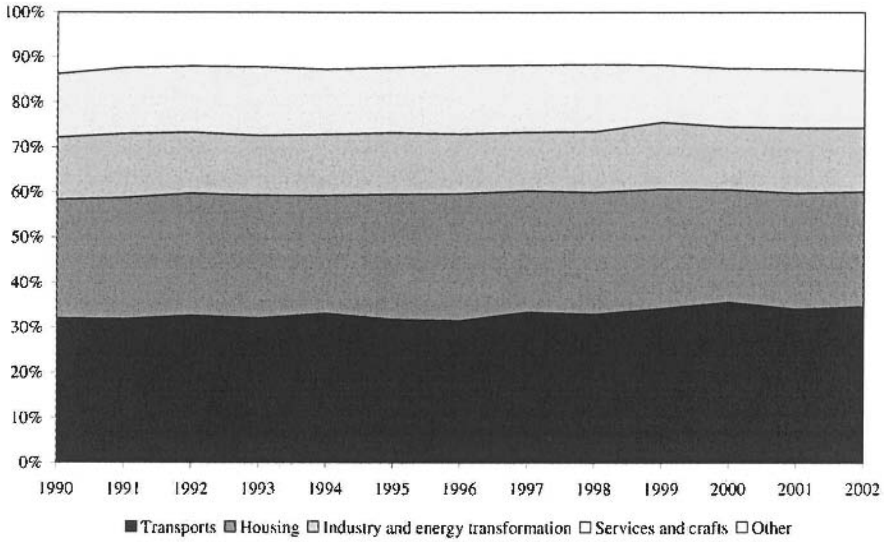

Figure 2.1. Main sources of CO_2 emissions

power plants. The production of thermal power stations has been insignificant throughout the twentieth century. Of course, the high shares of hydropower and nuclear in electricity generation help keep down CO_2 emissions. However, electricity represents only 22% of total final energy consumption of 855.3 PJ in 2000. The bulk share is that of oil products and they are entirely imported.

The drawback of this good performance is that it will be quite costly to further reduce the CO_2 intensity of the Swiss economy. Even the 8% target set in the Kyoto Protocol would be very demanding if economic growth were not so sluggish. Indeed, it is generally recognized that the marginal abatement cost for Switzerland is among the highest in OECD countries (for example, see Kram and Hill, 1996; Bahn et al., 1998, and Bernard et al., 2004b). On the other hand, Switzerland has additional incentives for reducing its use of fossil energy, namely reducing its imports and its dependency on world oil supply.

In many European countries, heavy industry bears the bulk of CO_2 emissions reductions. This is not possible in Switzerland and therefore the other sectors, most notably transportation and housing, must also contribute their share. Efforts to curb fuel consumption in the transportation sector meet fierce resistance by the oil sector, car owners and their organizations. Better results are obtained in the housing sector.

Table 2.1. Determinants of energy demand by housing sector and CO_2 emissions

	Mean 1991–92	Mean 2001–02	% change
Population (mio)	6.84	7.26	6.2%
Number of dwellings (mio)	3.19	3.61	13.1%
Mean surface of occupied dwellings (m^2)	93	106	14.0%
Final energy consumption (PJ)	243.3	239.2	−1.7%
CO_2 emissions by housing sector (Mt)	12.4	11.3	−9.0%

Notes: data from Swiss federal energy office and statistical office.
Surface of dwellings is from 1990 and 2000 censuses.

Table 2.2. Energy mix in housing

	1990 (TJ)	% total	2003 (TJ)	% total
Light fuel oil	139170	61.1	129540	52.2
Electricity*	47570	20.9	60040	24.2
Natural gas	25620	11.3	40330	16.2
Biomass	8430	3.7	8500	3.4
Distance heating*	4400	1.9	5220	2.1
Other renewables*	1820	0.8	4500	1.8
Coal	650	0.3	130	0.1

Source: Based on OFEN (2003);
Energy bearers marked with a * are not counted in CO_2 emissions of housing sector.
Distance heating is generally obtained from incinerating household waste.

CO_2 emissions by the housing sector declined from 12.4 Mt in 1991 and 1992 to 11.3 Mt in 2001 and 2002 (Table 2.1). This was obtained in spite of growing population, a number of dwellings that grew even more in number and in size.

The reduction in CO_2 emissions was obtained both through a reduction in energy consumption and changes in the energy mix. The latter is illustrated in Table 2.2. Light fuel oil remains the main energy source but natural gas is growing.

Regulation varies from canton to canton. In several cantons, new builders and owners who renovate are required to insulate their buildings and to install individual energy meters in each dwelling. Severe restrictions apply to air conditioning and electric heating. On the other hand, no demands are imposed on older buildings. Heating oil is virtually exempted from the fuel tax that adds about 76 Swiss cents to the liter of diesel, the equivalent motor fuel.

For older buildings and in the cantons that impose no regulation, the main instruments used to reduce fossil energy consumption by the housing sector are financial incentives and information. Small incentives are provided for the use of renewable energy and better insulation. The "Energy 2000" and "SwissEnergy" programmes provide technical assistance and promote a label for buildings with low energy consumption.

Such incentives are often offset by rent regulation.[2] Indeed, investments to reduce energy consumption cannot be passed on to the tenants who benefit from the lower energy expenses. Nor have the tenants any influence on decisions to renovate or not.

Thus, there remains a large potential for energy savings in the housing sector, a sector that still contributes one fourth of all CO_2 emissions. The technologies are available for improvements at relatively low marginal cost.

3. GEMINI-E3

The GEMINI-E3 is a dynamic-recursive CGE model that represents the world economy in 21 regions (including Switzerland) and 14 sectors. It incorporates a highly detailed representation of indirect taxation (Bernard and Vielle, 1998). GEMINI-E3 is formulated as a Mixed Complementarity Problem (MCP) using GAMS with the PATH solver (Ferris and Pang, 1997; Ferris and Munson, 2000). GEMINI-E3 is built on a comprehensive energy-economy data set, the GTAP-5 database (Hertel, 1997), that expresses a consistent representation of energy markets in physical units as well as a detailed Social Accounting Matrix (SAM) for a large set of countries or regions and bilateral trade flows. It is the fourth GEMINI-E3 version in this succession that has been especially designed to calculate social marginal abatement costs (Bernard and Vielle, 2003) (MAC, i.e., the welfare loss of a unit increase in pollution abatement). The original version of GEMINI-E3 is fully described in Bernard and Vielle (1998).[3] Updated versions of the model have been used to analyze the implementation of economic instruments for GHG emissions in a second-best setting (Bernard and Vielle, 2000), to assess the strategic allocation of GHG emission allowances in the EU-wide market (Viguier et al., 2004), to analyze the behavior of Russia in the Kyoto Protocol (Bernard et al., 2003, 2004), and to assess the costs of Kyoto for Switzerland with and without international emissions trading (Bernard et al., 2004b).

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[2] Two thirds of Swiss households live in rental dwellings, mostly in multi-family buildings.

[3] for a complete description of the model see our web site and the technical document downloadable at: http://ecolu-info.unige.ch/~nccrwp4/GEMINI-E3/HomeGEMINI.htm.

Beside a comprehensive description of indirect taxation, the strength of the model is to simulate all relevant markets: e.g., commodities (through relative prices), labor (through wages), and domestic and international savings (through rates of interest and exchange rates). Terms of trade (i.e., transfers of real income between countries resulting from variations of relative prices of imports and exports), and then "real" exchange rates can be accurately modeled.

Time periods are linked in the model through endogenous real rates of interest determined by the equilibrium between savings and investment. National and regional models are linked by endogenous real exchange rates resulting from constraints on foreign trade deficits or surpluses.

The main outputs from the GEMINI-E3 model are, by country and annually: carbon taxes, marginal abatement cost and price of tradable permits when relevant — effective abatement of CO_2 emissions, net sales of tradable permits (when relevant), total net welfare loss and components (net loss from terms of trade, pure deadweight loss of taxation, net purchases of tradable permits when relevant), macroeconomic aggregates (e.g., production, imports and final demand), real exchange rates and real interest rates, and industry data (e.g., change in production and factors of production).

For each sector the model computes the total demand (Y_{ir}) that includes household consumption (HC_{ir}), government consumption (GC_{ir}), exports (EX_{ir}), investment (IV_{ir}), and intermediate uses (IC_{ikr}):

$$Y_{ir} = \mathrm{HC}_{ir} + \mathrm{GC}_{ir} + \mathrm{EX}_{ir} + \mathrm{IV}_{ir} + \sum_k \mathrm{IC}_{ikr} \tag{2.1}$$

where i, r, and k stand for sectors, regions, and products respectively.

Total demand is then divided between domestic production (X_{ir}) and imports (M_{ir}). The model employs a convention that is widely used in modeling international trade: the Armington assumption (Armington, 1969). Under this convention a domestically produced good is treated as a different commodity from an imported good produced in the same industry.

$$X_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot \alpha^x_{ir} \cdot \left[\frac{\mathrm{PY}_{ir}}{\lambda^x_{ir} \cdot \mathrm{PD}_{ir}}\right]^{\sigma^x_{ir}} \tag{2.2}$$

$$M_{ir} = Y_{ir} \cdot \lambda^x_{ir} \cdot (1 - \alpha^x_{ir}) \cdot \left[\frac{\mathrm{PY}_{ir}}{\lambda^x_{ir} \cdot \mathrm{PI}_{ir} \cdot (1 + \kappa^i_{ir})}\right]^{\sigma^x_{ir}} \tag{2.3}$$

where PY_{ir} represent the price of good (without indirect taxation), PD_{ir} is the price of domestic production, and PI_{ir} is the price of imports; σ^x_{ir}, α^x_{ir}, λ^x_{ir}, and κ^i_{ir} represent the CES parameters, respectively, the

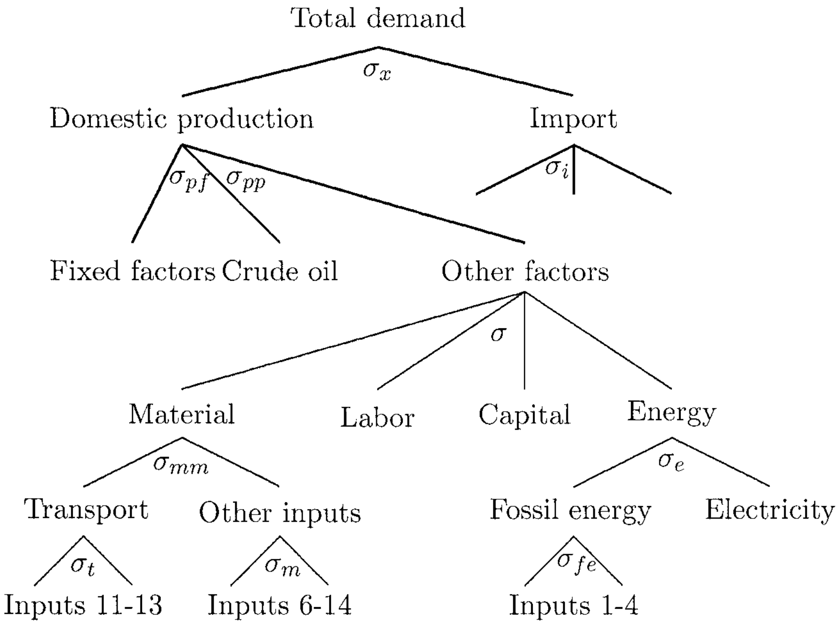

Figure 2.2. Structure of the production sector in GEMINI-E3

elasticity of substitution, the share parameter, the technology shifter, and the duty rates.

Figure 2.2 represents the structure of the production sector in the model. Production technologies are described using nested CES functions.

Household's behavior consists in three interdependent decisions: (1) labor supply; (2) savings; and (3) consumption of the different goods and services. In GEMINI-E3, we suppose that labor supply and the rate of saving are exogenously set. The utility function is assumed to have a Stone-Geary form (Stone, 1983) which is written as:

$$u_r = \sum_i \beta_{ir} \cdot \ln(\mathrm{HC}_{ir} - \phi_{ir}) \tag{2.4}$$

where ϕ_{ir} represents the minimum necessary purchases of good i, and β_{ir} corresponds to the marginal budget share of good i.

Maximization of (2.4), under the budgetary constraint (2.5) given below, where HCT_r represents the total expenditure for households consumption, and where PC_{ir} is the price of consumption which equals to the price of good plus the indirect taxes,

$$\mathrm{HCT}_r = \sum_i \mathrm{PC}_{ir} \cdot \mathrm{HC}_{ir}, \qquad (2.5)$$

yields

$$\mathrm{HC}_{ir} = \phi_{ir} + \frac{\beta_{ir}}{\mathrm{PC}_{ir}} \cdot \left[\mathrm{HCT}_r - \sum_k (\mathrm{PC}_{kr} \cdot \phi_{kr})\right]. \qquad (2.6)$$

4. ETEM-Switzerland

ETEM-SWI (Energy-Technology-Environment model for Switzerland) is a linear programming model of the production, trading, transformation, distribution and end-uses of various energy forms in Switzerland. It belongs to the family of the well-known techno-economic MARKAL[4] models, developed under the auspice of the international consortium of Energy Technology Systems Analysis Programme (ETSAP). The current version of ETEM-SWI uses the same structure and analytical tools as the World MARKAL model described in Labriet et al. (2004)) and Kanudia et al. (2005). It also belongs to the same family of MARKAL models as the MARKAL model for Switzerland (Bahn et al., 1998) and Geneva (Fragnière and Haurie, 1996a,b).

ETEM-SWI computes a supply-demand partial economic equilibrium on Switzerland's energy markets that maximizes net total surplus (i.e., the sum of producers' and consumers' surpluses) over 2000–2050, while satisfying the demands for energy services (demand-driven model) and a number of constraints (e.g., environmental constraint). The model, like most equilibrium models, assumes perfectly competitive energy markets, except in cases where user-defined, explicit special constraints are added (e.g., limits to the penetration of some technologies, see below). Moreover, the model is run in a dynamic manner, assuming perfect information and foresight, so that investment decisions are made with full knowledge of the future.

The total cost of the system includes, at each time period: annualized investments in technologies, fixed and variable annual operation and maintenance costs of technologies; cost of energy imports and domestic resource production; revenue from energy exports; delivery costs; losses incurred from reduced end-use demands; and taxes and subsidies associated with energy sources, technologies, and emissions. The outputs

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[4] MARKAL (MARKet ALlocation) is a dynamic linear programming model of the energy system and the environment of a given country or region (Fishbone and Abilock, 1981; Berger et al., 1992; Kram and Hill, 1996; Kypreos, 1996; Loulou and Kanudia, 2002).

from the model are: investments in technologies, operating levels for each type of technology, in each time period, levels of primary resource availability, and levels of energy carrier purchased from and/or sold to other regions. Of course, emissions and energy mix result from all these decisions.

ETEM-SWI is technology rich with more than 1600 technologies. The reference energy system is disaggregated into five energy consumption sectors (residential RES, commercial COM, agriculture AGR, industrial IND, transportation TRA), plus a non-energy use of energy/material products NEU, and two energy/supply sectors (electricity ELC and upstream/refinery UPS). New technologies are generally the same as those used in the Western Europe MARKAL model used in Kanudia et al. (2005).

The model includes 42 demands for energy services (19 in residential/commercial, 16 in transportation, 6 in industry, 1 in agriculture), such as vehicle-kilometers traveled by car, tonnes of aluminum to produce, etc. Price-elasticities of demands are also accounted for, so that the model captures a major element of the interaction between the energy system and the economy, and therefore, it goes beyond the optimization of the energy sector only since both the supply options and the energy service demands are endogenously computed by the model. Of course, this still falls short of computing a general equilibrium: to do so would require a mechanism for adjusting the main macroeconomic variables as well, such as consumption, savings, employment, wages, and interest rates, which the model does not represent.

The reader may refer to Labriet et al. (2004) and Kanudia et al. (2005) for more information on the general philosophy, equations and structure of the model. The rest of this section focuses on the specific characteristics of ETEM-SWI.

4.1 The existing energy system

The calibration of the model to an initial year reflecting historical data is a crucial task for building ETEM-SWI as well as any MARKAL model. Indeed, this calibrated initial energy system defines the existing stock of energy equipment, which, combined with the available future technologies and the primary energy potentials, will influence the model's future energy decisions. The fuel consumption per sector (Table 2.3) and the secondary energy production (electricity sector, refinery) are based on

Table 2.3. Sectoral energy consumption used in ETEM-SWI in 2000 (TJ)

	Oil	Elec.	Gas	Coal	District heating	Biomass	Other renew	Total
RES	121.5	56.8	37.9	0.4	5.1	8.54	3.5	233.6
IND	44.8	63.9	36.9	5.3	5.3	19.7	0.1	176.0
COM	52.5	55.2	20.4	0.0	3.1	3.3	0.6	135.1
TRA	294.6	9.2	0.2	0.0	0.0	0.0	0.0	304.0
NEU	16.4	0.0	0.0	0.0	0.0	0.0	0.0	16.4
NS[a]	4.7	0.0	5.3	0.0	0.0	0.0	0.0	10.0
SD[b]	5.7	3.4	0.0	0.0	0.0	0.9	0.4	10.4
Total	540.2	188.5	100.7	5.7	13.5	32.3	4.6	885.6

[a] NS: non-specified.

[b] SD: statistical difference, including agriculture.

Table 2.4. GDP and population projections for Switzerland

	2000	2010	2020	2030	2040	2050
GDP (billions US$2000)	247	306	358.6	418.6	475.8	517
Population (millions)	7.2	7.3	7.4	7.4	7.3	7.2

various Swiss national statistics[5] for 2000 or on the energy statistics provided by IEA (2002b)) if national statistics are not available. It must be noted that no primary energy production exists in Switzerland. The calibration of the residential sector is detailed in Section 5.1. The assumptions related to the other sectors are available upon request.

4.2 The projections of demands

The projections of end-use demands result from economic and demographic drivers (see Table 2.4) applied to the 2000 values in conjunction with assumptions on the sensitivity of service demands to the drivers, so that the projections are calibrated to the available national statistics. Transportation demands are based on Jochem et al. (2002) and OFEN (2000a); industry demands are based on BasicsAG (1996); by default, agriculture, residential and commercial sectors use the same sensitiv-

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[5] National statistics from OFEN (2000b); electricity related data from OFEN (2000c,d), and Prognos (2000)); industry data from BasicsAG (1996); buildings data from Brunner et al. (2001) and Kessler and Iten (2003); transportation data from OFEN (2000a) and Jochem et al. (2002); and emissions data from UNFCCC (2002).

ity of service demands to the drivers as the Western Europe MARKAL model (Kanudia et al., 2005).

4.3 Techno-energy assumptions

This section describes the most important techno-energy characteristics used to model the Swiss energy system. First, given the relatively small size of the Swiss economy, we assume that changes in the level of Swiss exports and imports have no effects on the prices of internationally traded energy commodities. The latter are therefore exogenously fixed. Second, in the electricity sector both the nuclear production and the level of imports/exports are crucial in describing the future electricity system as well as the future GHG emissions of Switzerland. As regards nuclear power plants, we adopt the base case scenario proposed by Prognos (2000), assuming that the nuclear plants operate until the end of their lifetime (50 to 60 years). The installed nuclear capacity is 3.08 GW until 2015, decreases to 2.08 GW in 2025 (closure of Beznau I, II and Mühleberg between 2020 and 2025), and no nuclear capacity remains from 2040 on. (In the full ETEM scenarios, Nuclear plants are replaced, at the end of their life by combined cycle gas/oil plants in the reference scenario, and by wind plants when CO_2 emissions are limited.) As regards electricity trade, the amount of exports and the minimal level of imports are fixed, reflecting the expected evolution of the purchasing agreements. The level of exports and the price of exports and imports are fixed to the levels proposed by Prognos (2000), while the minimal level of imports is smaller than the projections proposed by Prognos (2000), but the model is kept free to decide to import more electricity depending on carbon constraints and electricity prices. The effects of nuclear production and electricity trade on the CO_2 emissions deserve more attention in future work (sensitivity analysis).

In transportation, the minimal shares of natural gas (5% in 2050) and electricity (3% in 2050) in the total energy consumed by cars and light trucks are exogenously controlled. These constraints aim at reflecting the transportation policies in favor of alternative fuels either already decided or independent of climate policies. In industry, each demand segment includes: boiler, process heat, machine drive, electro-chemical process, and other processes. Feedstocks are included only in the chemical sub-sector. User-defined explicit constraints account for non-economic consumer behaviors that are outside the scope of the model. They limit the speed of energy and technology changes, and are progressively relaxed in future periods, so that enough flexibility is available for energy substitution and technology change. But recall that the industry-related CO_2 emissions

Table 2.5. Electricity production by fuels, imports and exports in the base case (TWh)

	2000	2010	2020	2030	2040	2050
Mix gas/oil	0.00	0.00	0.00	0.00	3.61	3.89
Gas	0.28	0.28	0.00	0.00	0.00	0.00
Oil	0.00	0.00	0.00	0.00	0.00	0.00
Nuclear	25.83	25.83	23.33	17.50	0.00	0.00
Hydro	37.22	37.22	37.22	37.22	39.44	39.44
Biofuels	1.39	1.11	1.94	2.78	3.06	3.61
Wind	0.00	0.00	0.00	0.00	0.00	0.00
Total	64.72	64.44	62.50	57.50	46.11	46.94
Exports	47.30	36.06	26.67	19.39	17.97	17.97
Imports	37.00	34.03	25.53	17.03	16.67	16.67

as well as the abatement potential are very small. Finally, the assumptions related to the residential sector are described in Section 5.1, since this sector is at the heart of the proposed coupling between ETEM-SWI and GEMINI-E3.

5. The hybrid model

The basic idea is to create a dialogue between the two complementary models. On one side, we use a reduced version of the CGE model, GEMINI-E3S, where the residential sector is removed and will be exogenously defined by a bottom-up model. On the other side, we use a reduced ETEM-SWI, called ETEM-RES, that represents only the residential sector, and where projections of useful energy demand, fuel prices and carbon price (tax) are provided by GEMINI-E3S. Rather than endogenizing energy demand by using price elastic demand formulations as in Loulou and Kanudia (2002), we obtain energy demands and the associated prices directly from the CGE model. In this section, we describe briefly the two reduced models, and the coupling technique.

5.1 The reduced GEMINI-E3S model

For the coupling of GEMINI-E3 with a bottom-up model we use an aggregated version of the model in 6 regions rather than 21 (see Table 2.6). The reference case for the different regions is closely calibrated on projections of CO_2 emissions, energy consumption, GDP, and population provided by EIA (2003a) for the years 2000 to 2025. After 2025, we have supposed a convergence of GDP growth to 2% per year for developed regions and 2.5% per year for developing regions at the end of the baseline projection. World greenhouse gas emissions are projected to reach 13Gt of carbon equivalent in 2020 and 16GtC equivalent in 2050 (Bernard et al., 2004a).

In the case of Switzerland, we have defined a baseline scenario that includes existing laws and regulations that have an impact on future domestic CO_2 emissions (Bernard et al., 2004b). This baseline is fully consistent with population, GDP, energy consumption, and CO_2 emissions growth projected by the Swiss government in a scenario "with measures implemented" (Bundesamt fur Energie, 2001; UNFCCC, 2002). This baseline scenario is also comparable with the one obtained from ETEM-SWI and ETEM-RES (see below).

Introducing energy consumption from ETEM-RES model needs two steps. The first step is to separate household energy consumption into residential and non-residential (mainly transportation). We have supposed that household consumptions of coal, natural gas and electricity are totaly used for residential purposes. For refined petroleum consumption we have to breakdown energy consumption between transportation and housing (mainly heating). We have used energy consumptions from IEA energy balances (OFEN, 2000b) and energy prices (IEA, 1998). The second step is to modify the standard Stone-Geary utility function (see equation (2.6) in section 3). The solution retained is to subtract from total household consumption (HCT_r) the purchase of energy for residential purposes, and to apply the Stone-Geary utility function to this new aggregate. This yields the following equation for non-energy consumption goods (i.e., food, clothing, services, etc)[6]:

$$\mathrm{HC}_{ir} = \phi_{ir} + \frac{\beta_{ir}}{\mathrm{PC}_{ir}} \cdot \left[\mathrm{HCT}_r - \sum_k (\mathrm{PC}_{kr} \cdot \phi_{kr}) - \sum_l (\mathrm{PC}^R_{lr} \cdot \mathrm{HC}^R_{lr})\right] \qquad \forall i = 6, \ldots, 14 \text{ and } r = 3 \quad (2.7)$$

where PC^R_{lr} and HC^R_{lr} represent the price and consumption of energy for residential activities.

For coal, natural gas and electricity consumption we replace the standard formula by the variable computed on the basis of ETEM-RES results:

$$\mathrm{HC}_{ir} = \mathrm{HC}^R_{ir} \qquad \forall i = 1, 2, 3, 5 \text{ and } r = 3 \qquad (2.8)$$

---

[6] where i, r respectively stand for sectors and regions (i.e., $r = 3$ stands for Switzerland, see Table 2.6).

Table 2.6. Dimensions of the GEMINI-E3S model

Countries or Regions		Sectors	
Germany	DEU	**Energy**	
France	FRA	01	Coal
Switzerland	CHE	02	Crude Oil
Italy	ITA	03	Natural Gas
Other European Countries	OEU	04	Refined Petroleum
Rest of World[b]	ROW	05	Electricity
		Non-Energy	
		06	Agriculture
		07	Mineral products
		08	Chemical Rubber Plastic
		09	Metal and metal products
		10	Paper Products Publishing
		11	Transport n.e.c. (road and railway)
		12	Sea Transport
		13	Air Transport
		14	Other Goods and services

[b] All countries not included elsewhere.

where HC^R_{ir} are computed by the following equation :

$$\mathrm{HC}^R_{ir} = \overline{\mathrm{HC}^R_{ir}} \cdot \frac{\mathrm{CF}_{ir}}{\overline{\mathrm{CF}_{ir}}} \quad \forall i = 1, \ldots, 5 \tag{2.9}$$

where $\overline{\mathrm{HC}^R_{ir}}$ represents residential energy consumption in the reference case in volume (i.e., in dollars at constant price), and $\overline{\mathrm{CF}_{ir}}$ and CF_{ir} are the energy consumptions (in joules) computed by ETEM-RES in the reference case and in the policy scenario (see Section 5.3). We thus apply in GEMINI-E3S percentage changes computed by the ETEM-RES model for energy consumption.

Finally we have to breakdown households' consumption of refined petroleum into transport and residential purposes (HC^R_{ir}) :

$$\mathrm{HC}_{ir} = \mathrm{HC}^R_{ir} + \phi_{ir} + \frac{\beta_{ir}}{\mathrm{PC}_{ir}} \cdot \left[\mathrm{HCT}_r - \sum_k (\mathrm{PC}_{kr} \cdot \phi_{kr}) - \sum_l (\mathrm{PC}^R_{lr} \cdot \mathrm{HC}^R_{lr})\right]$$
$$i = 5 \text{ and } r = 3 \tag{2.10}$$

ϕ_{ir} and β_{ir} are recalibrated on the basis of this new system of equations.

5.2 The reduced ETEM-RES model

ETEM-RES consists of the residential sector of ETEM-SWI. It includes 11 demand segments which cover the needs in energy for the housholds (excluding personal transportation): heating, cooling, lighting, cooking, water heating, refrigerators and freezers, cloth washers, cloth dryers, dish washers and miscellaneous electric energy. The existing total energy consumption by the residential sector is based on OFEN (2000b) and on the IEA database (IEA, 2002a). Table 2.7 shows the exogenous fuel split across the different end-use segments, inspired by Brunner et al. (2001) for electricity, by Kessler and Iten (2003) for space and water heating, and by the Western Europe MARKAL model as used in Labriet et al. (2004) and Kanudia et al. (2005) when Swiss statistics were unavailable.

For each end-use segment, technologies are in competition to satisfy the demand. For example, lighting may be satisfied by incandescent lamps, halogens, fluocompact lamps, etc.; or space may be heated with standard natural gas burner, improved natural gas burner, natural gas heat pump, geothermal heat pump, woodstoves, etc.

Technologies are characterized by their efficiency, annual utilization factor, lifetime, investment and operation costs. New technologies progressively replace existing technologies when they are cost-efficient (competitive in terms of comparison of NPVs) and the latter reach the end of their lifetime or when environmental policies force such a replacement. However, some exogenous constraints are added to reflect consumer behaviors and to avoid any abrupt and improbable technology change: they control either the energy mix of end-use consumptions (e.g., minimum level of electric technologies in cooling), or the penetration of some technologies (e.g., minimum level of standard electric heat pump cooling). The constraints are progressively relaxed in future periods. Finally, a delivery cost for natural gas is added to account for new investments in distribution infrastructure.

5.3 The coupling technique

5.3.1 Possible dialogue between the two types of models.

One possible way to couple a CGEM and an ETEM would involve an exchange of information in one direction (from CGEM to ETEM) concerning useful demands and imported energy prices[7] and in the other direction (from ETEM to CGEM) about marginal abatement cost (MAC)

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[7] The World economic model should provide information about the world demand for different energy forms and hence an indication of the relative prices of different forms of imported fuels.

Table 2.7. Initial fuel split across energy end-uses in the residential sector (%)

	NGA	DST	HFO	KER	COA	LPG	BIO	ELC	HET	GEO	SOL
Space heating	79	86	100	100	89.9	68	97.7	17	100	85.9	
Space cooling								5		14.1	
Water heating	16	14			8.8	23	2.3	10			100
Freezers								14			
Clothes Drying								6			
Cooking	5				1.3	9		5			
Clothes washers								1			
Dish-washer								1			
Other Energy		0				0			0		
Misc. Elc Energy								32			
Lighting								9			

curves[8]. Unfortunately this approach is confronted to serious implementation difficulties when it comes to the correct evaluation of the MAC curves needed to run the CGEM. The marginal costs computed by ETEM are related to the dual values associated with emissions upper bounds. They are based on the intertemporal perfect foresight optimization scheme implemented in MARKAL. Often these dual values in ETEM change drastically from one period to the next and it is not obvious to derive the stable MAC curves needed for each time period in the CGEM. Furthermore, it is not the dual value associated in ETEM with one level of abatement that is needed but the whole curve of dual values for different possible abatement levels. In Lavigne et al. (2000), a method is proposed for exchanging local information concerning these MAC curves between models[9]; however we are not aware of a successful use of these methods to couple an ETEM and a CGEM.[10]

To circumvent these difficulties we have implemented a coupling via a different type of dialogue between the two models. The CGEM still sends estimates of useful demands and energy prices to the ETEM; it also defines the carbon taxes that will be applied in the ETEM optimiza-

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The Swiss CGEM will provide information about economic activity in the different sectors and hence the useful demands.

[8] MAC curves are an essential part of CGEM when they address the issue of climate policy assessment. This information summarizes the technical substitutions that should take place to obtain the desired emissions abatement.

[9] They considered in this way the linkage of linear models of supply and demand.

[10] The study realized at MIT attempted a linkage between the transportation sector in MARKAL and the CGEM EPPA (Schafer and Jacoby, 2003). The link was very weak, as the MARKAL model only served to delineate, through a sequence of runs, a global shape for the MAC curve.

tion run.[11] For the CGEM the ETEM is a "black box" which sends back a set of final energy demands and carbon emissions from the residential sector. This way we use marginal abatement costs from the CGEM for all sectors, except for the housing sector. For housing, we use the ETEM to mimic the technology/energy choices of economic agents in the residential sector facing market prices and carbon taxes. In the CGEM, the modeling of household consumption — which is based on a Linear Expenditure System (LES) corresponding to the Stone-Geary utility function — has to be modified (see above). In GEMINI-E3S, households' energy consumption for housing is set exogenously on the basis of the fuel mix obtained from ETEM. Non-energy consumption for housing is supposed to change in response to changes in relative household consumption prices (including fuel prices) but is not modified by the energy mix resulting from technology choices in ETEM.

5.4 The coupling realized in this case study

The coupling variables are listed in Table 2.8.

Since the energy prices $PE_{t,k}$ are not expressed in the same unit in the two models we apply a "percentage change" procedure. For example if GEMINI-E3S computes that the price of coal is increasing by 10% with respect to the baseline we applied the same variation for the price of coal used by ETEM-RES. The same procedure is used for $CF_{t,k}$ (see equation 2.9). The residential useful energy demand implemented in ETEM-RES, $CE_{t,k}$, is indexed on total household consumption computed by GEMINI-E3S. So we suppose that the budget share of residential services (cooking, lighting, heating, etc) does not differ from the baseline scenario. The procedure to couple the two models is summarized below and in Figure 2.3:

1. Run GEMINI-E3S on the basis of an emission reduction profile (see Policy Scenarios) in order to get starting values for carbon taxes $T_{t,0}$, energy prices $\mathrm{PE}_{t,0}$, and useful energy demands in the residential sector $\mathrm{CE}_{t,0}$.
2. Run ETEM-RES using values for $T_{t,0}$, $\mathrm{PE}_{t,0}$, and $\mathrm{CE}_{t,0}$ from GEMINI-E3S, and get starting values for final energy demands $\mathrm{CF}_{t,0}$ and carbon emissions $C_{t,0}$ in the residential sector.
3. Run the GEMINI-E3S model with estimates for $\mathrm{CF}_{t,0}$ and $C_{t,0}$ from ETEM-RES in order to get new carbon taxes $T_{t,1}$, energy

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[11] Note that the ETEM run is made without emissions constraints, but realizes cost minimization under a given carbon tax system.

prices $\mathrm{PE}_{t,1}$ and useful energy demand $\mathrm{CE}_{t,1}$ in the residential sector up to 2050.

4. Run ETEM-RES using the new data from GEMINI-E3S ($T_{t,1}$, $\mathrm{PE}_{t,1}$, and $\mathrm{CE}_{t,1}$), and obtain new estimates for the fuel mix $\mathrm{CF}_{t,1}$ and carbon emissions $C_{t,1}$.
5. Run GEMINI-E3S with $\mathrm{CF}_{t,1}$ and carbon emissions $C_{t,1}$ and get $T_{t,2}$, $\mathrm{PE}_{t,2}$, and $\mathrm{CE}_{t,2}$; etc.
6. Use the stopping criterion[12] defined in Eq. (2.11) for convergence, where $T_{t,k}$ represents carbon prices at time t from GEMINI-E3S in iteration k.

$$\Phi = \sqrt{\sum_{1}^{t}(T_{t,k} - T_{t,k-1})^2} \leq \epsilon = 0.01 \tag{2.11}$$

At convergence, one has a system of carbon taxes determined by the CGEM that yields the desired abatement levels in the whole economy and for which, the carbon emissions and fuel mix in the residential sector is the one selected by economic agents when they minimize the total discounted cost.

Table 2.8. List of coupling variables

$T_{t,k}$: carbon taxes
$\mathrm{PE}_{t,k}$: energy prices
$\mathrm{CE}_{t,k}$: useful energy demand in the residential sector,
$\mathrm{CF}_{t,k}$: final energy consumption by fuel type
$C_{t,k}$: carbon emissions
t : stands for time period
k : stands for iteration number

5.5 Scenarios and results

5.5.1 Reference case. The reference case represents a situation where no energy or environment policies apply beyond the already enforced laws and regulations. As described previously, the reference case is built on three essential assumptions that are likely to have an effect on energy consumption and carbon emissions:

- The economic and demographic projections (see Section 4.2);

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[12] A gap $\epsilon = 0.01$ means that one declares convergence when two successive tax schedules differ by less than one cent other the whole period.

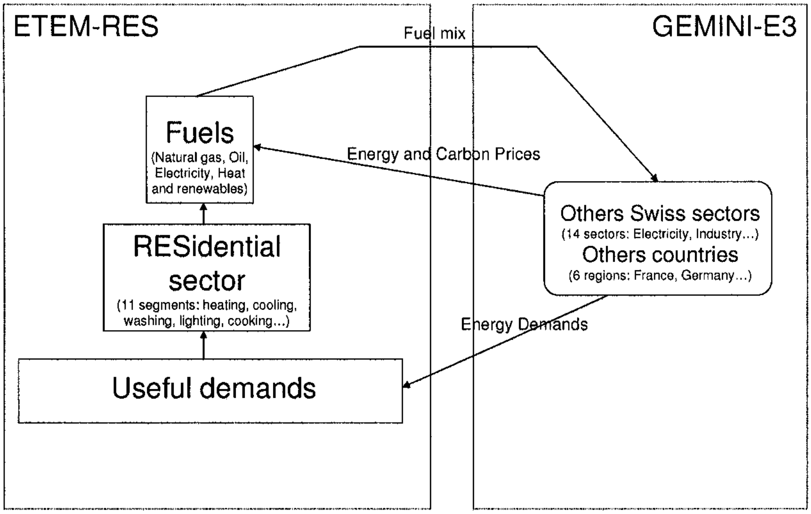

Figure 2.3. ETEM-RES and GEMINI-E3S overview

- The gradual increase of energy efficiency, in response to energy legislations and energy efficiency programmes such as the Federal programm "Energy Switzerland";
- The level of nuclear power plants and of exports/imports (see Section 4.3).

Figures 2.4 and 2.5 illustrate the resulting energy mix and carbon emissions obtained from ETEM-SWI and used to calibrate the reference case in GEMINI-E3.

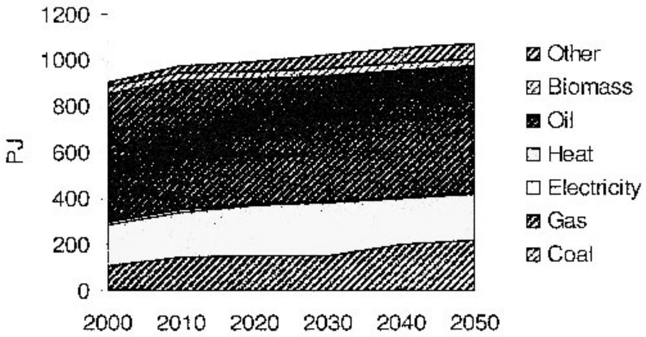

Figure 2.4. Energy mix obtained with ETEM-SWI in the reference case

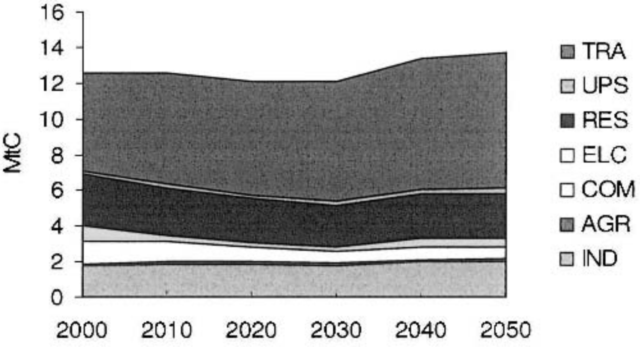

Figure 2.5. CO_2 emissions obtained with ETEM-SWI in the reference case

5.5.2 Policy scenarios. In this study, we selected two policy scenarios to mitigate global GHG emissions constraint in the long run:

S20: world CO_2 emissions are assumed to be reduced linearly in order to obtain a 20% reduction from the reference case by 2050. For simplicity, we assume that emissions quotas are allocated among countries in proportion to emission in the reference case (20% target for each region, including Switzerland).[13] Finally, each country or region is supposed to reach its reduction target through a uniform CO_2 tax without exemptions and without international emissions trading.

S40: This scenario is the same as the previous one, except that the reduction target is 40%.

5.5.3 Simulation results. In Table 2.9 we show that convergence has been reached after four iterations under the two policy scenarios. In Figure 2.6, we plot carbon taxes $T20_{t,k}$ and $T40_{t,k}$ obtained from 2000 to 2050 under the 20% and the 40% reduction target scenarios, respectively. The carbon taxes $T20_{t,0}$ and $T40_{t,0}$ are obtained, for the two reduction scenarios, from GEMINI-E3S when one uses the starting values $CF_{t,0}$ and $C_{t,0}$ provided by ETEM-RES. The values $T20_{t,4}$ and $T40_{t,4}$ are carbon taxes obtained in the last (4th) iteration of the coupling process.

As shown on the graph, carbon taxes are expected to grow in Switzerland from \$70/tC in 2010 to \$414/tC in 2050 in the S20 scenario. When

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[13] The equity issue related with the sharing of the costs of the long term GHG emissions target across countries and regions have been considered elsewhere (Bernard et al., 2004a).

Table 2.9. Values of Φ in the two policy cases

	S20	S40
$k = 1$	121.13	481.70
$k = 2$	19.22	12.87
$k = 3$	2.77	0.05
$k = 4$	0.01	0.006

Table 2.10. Carbon taxes by region in the two policy cases in 2050 (in \$/tC)

	S20	S40
Switzerland	414	1362
Germany	197	755
France	292	1224
Italy	282	1106
Other European Countries	111	462
Rest of the World	45	174

CO_2 emissions are assumed to be reduced by 40% (S40), the carbon tax rises from \$138/tC in 2010 to \$1362/tC in 2050. At an international level (see Table 2.10) the results confirm (Kram and Hill, 1996; Bahn et al., 1998) that the marginal abatement cost (i.e., the carbon tax) for Switzerland is the highest even in comparison to other European countries.

In Figures 2.7, one can observe that the contribution of the Swiss residential sector to the reduction effort is rather low. In the S20 scenario, CO_2 emissions are reduced by 13% compared to the reference emissions in 2050. In the S40 scenario, CO_2 emissions are 26% below the reference emissions in 2050. By taking into account substitution and reduction options in the whole economy, the coupled model finds that abatement costs are relatively high in the residential sector compared to the other sectors and that emissions might be reduced at lower cost in other sectors.

One should also note that the CO_2 emissions targets are reached through inter-fuel substitutions rather than a drastic reduction of residential energy consumption. Compared to the reference case, energy consumptions are reduced by only 2.5% and 5% in 2050 in the S20 and S40 scenarios, respectively. It means that CO_2 emissions reductions are realized through changes in the fuel mix in the housing sector. Indeed, the 20% reduction required in the S20 scenario is mainly obtained

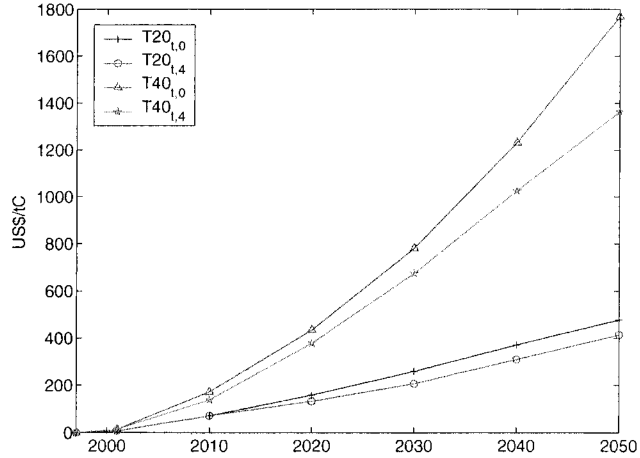

Figure 2.6. Carbon taxes in Switzerland under the two policy cases, 2000-2050 (in \$/tC). $T20_{t,0}$ and $T40_{t,0}$ correspond to carbon taxes obtained from GEMINI-E3S with starting values $CF_{t,0}$ and $C_{t,0}$ from ETEM-RES. $T20_{t,4}$ and $T40_{t,4}$ are carbon taxes resulting from the last iteration

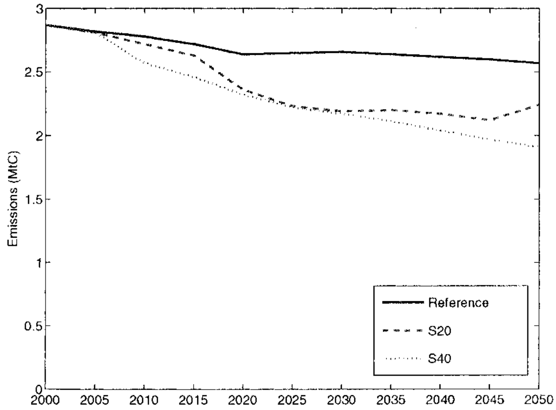

Figure 2.7. CO_2 emissions in the residential sector in the reference case, S20, and S40, 2000–2050 (in MtC)

through a switch from natural gas to electricity and biomass (see Figure 2.8). The basic story is the same when the carbon constraint is more severe (S40), except for a lower share of natural gas and a greater penetration of geothermal energy (i.e., heat pumps for space heating, space cooling, and to provide hot water).

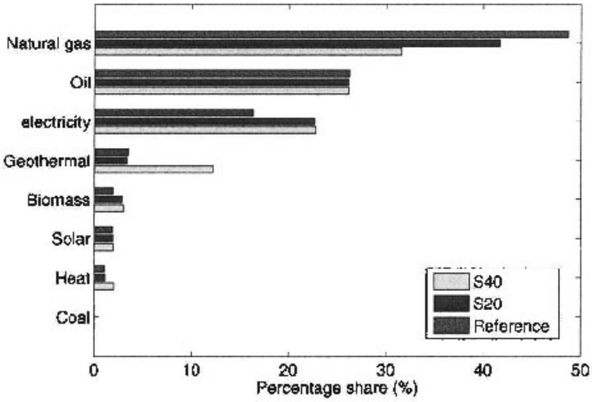

Figure 2.8. Energy consumption by fuel type in the residential sector in the reference case, S20, and S40, 2050 (in %)

In Figures 2.9 and 2.10, one can see that almost 70% of the demand for energy services (useful energy demand) in the housing sector would be for heating space in 2050. In the S20 scenario, space heating is mainly provided with natural gas (55%) and oil (32%). Geothermal energy and biomass represent only 4.5% and 2.8% of total energy consumption for space heating in 2050. When the emissions constraint is higher (S40), the consumption of natural gas for space heating is reduced (41%), and geothermal energy increases from 4.5% to 16.7%.[14]

6. Comparing GEMINI-E3, ETEM-ED-SWI, and the hybrid model

In order to evaluate the effects of coupling ETEM-RES and GEMINI-E3S. It is interesting to compare the simulation results coming from the hybrid model with the ones from the standard version of the two models, GEMINI-E3 and the ETEM model with elastic demand (ETEM-ED-SWI).

As shown in Table 2.11, the carbon tax with GEMINI-E3 and the coupled model are quite similar even if the tax is always smaller with the GEMINI-E3 model. In the S40 scenario, the residential carbon emission

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[14] The observed stability of oil share might seem counterintuitive and deserves some explanations. In the model, the consumption of oil for space heating and water heating is controlled by exogenous constraints, reflecting that fuel substitution associated to these service demands depends not only on economic factors but also on non-market parameters. Here, this constraint acts as a lower bound for oil consumption.

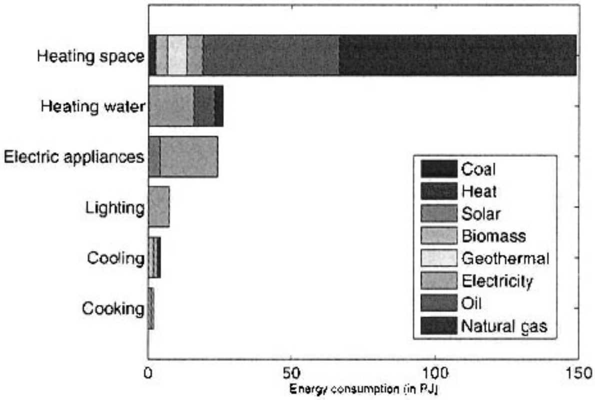

Figure 2.9. Useful energy demand under the 20%-reduction scenario, 2050 (in PJ)

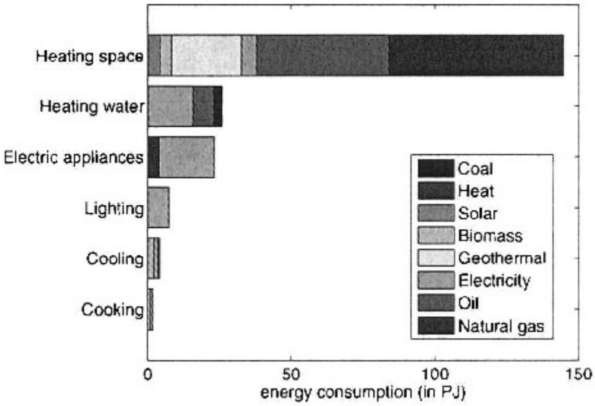

Figure 2.10. Useful energy demand under the 40%-reduction scenario, 2050 (in PJ)

abatement would be equal to 57% with the GEMINI-E3 model whereas the reduction would only be 26% with the hybrid model. The ETEM-RES module gives less substitutability of fossil fuel consumption in response to an increase of carbon taxes. Carbon prices must be increased more in the hybrid model in order to reach the same carbon emission reduction in percentage. A higher burden is thus put on the other energy consumption in the hybrid model (i.e., agricultural, industrial and transport energy consumption). The changes in energy consumption in the housing sector are also quite different in the two models, even if the ranking of the energy sources is similar: the two models find that electricity would be less affected and that natural gas would be more depressed.

Table 2.11. GEMINI-E3 versus hybrid model in2050

	Scenario S20		Scenario S40	
	Gemini-E3	Hybrid	S40 Gemini-E3	Hybrid
Carbon Tax (in \$/tC)	342	414	1142	1362
Residential Energy Consumption*				
Coal	−64.3%	−0.3%	−69.5%	−3.3%
Petroleum products	−14.6%	−2.8%	−35.2%	−5.4%
Natural Gas	−55.3%	−16.5%	−77.7%	−38.5%
Electricity	−1.4%	35.1%	−4.4%	32.2%
Residential Carbon Emission*	−36.2%	−11.4%	−57.6%	−26.1%

*Percentage change from the reference scenario in 2050.

For natural gas and refined petroleum consumption GEMINI-E3 gives more important reductions: −35% with GEMINI-E3 against −5.4% with the hybrid model for petroleum products in the scenario S40 and −77% against −38% for natural gas. Electricity consumption goes the opposite way: the hybrid model yields an important increase of electricity consumption (more than 30% in the two cases) whereas electricity consumption slightly decreases in the GEMINI-E3 configuration (less than 5% in the S40 scenario).

Simulations results show that marginal abatement costs tend to be higher in ETEM-SWI than in GEMINI-E3 in all sectors. At the same time, marginal abatement costs are relatively low in the residential compared to other sectors in the two models. Consequently, when the two models are combined in the hybrid model, one gets a lower contribution to the reduction effort from the residential sector compared to the case where the two models are used separately. In the S40 scenario, residential carbon emissions might be reduced by 26% in the hybrid model against 58% in the GEMINI-E3 model and 53% in ETEM-ED-SWI.

In Table 2.12, we compare numerical results from the hybrid model with results obtained from ETEM-ED-SWI when S20 and S40 carbon taxes are applied. Several remarks apply. First, transportation plays a crucial role in the overall emission reduction of Switzerland in both scenarios: the substitution of oil by biomass and by natural gas to a lesser extend, as well as the penetration of more efficient oil vehicles are observed, while electricity remains unchanged compared to the baseline scenario. Second, it is interesting to note that the share of residential in the overall emission reduction is higher in previous periods under S20 scenarios (for example, it reaches more than 65% of the reduction in

Table 2.12. ETEM-ED-SWI versus hybrid model in 2050

	% of total emission reduction		% of reference emissions	
	S20	S40	S20	S40
ETEM-ED-SWI				
Agriculture	0%	0%	0%	0%
Commercial	0%	2%	–1%	–15%
Electricity	10%	7%	–75%	–82%
Industry	12%	16%	–24%	–44%
Residential	8%	24%	–12%	–53%
Transport	70%	51%	–36%	–45%
Total	**100%**	**100%**	**–28%**	**–45%**
Hybrid model				
Residential	12%	12%	–11%	–26%

2025). Indeed, fuel substitution in residential and industry sectors is preferred to fuel substitution in transportation when the low CO_2 tax is applied. It means that the penetration of biomass vehicles becomes a competitive abatement option in the short run only under higher levels of CO_2 tax. In other words, abatement options in residential might represent a transition to alternative transportation technologies. Finally, emissions are strongly reduced in the electricity sector (gas/oil combined cycle plants are replaced by wind plants) in both scenarios, while the emission reductions by industry and housing sectors are far larger when S40 is implemented. However, it must be noted that large reductions from the reference case (right-hand columns of table 2.12) may represent small absolute emission reductions (e.g., emissions reduction from the electricity sector) (left-hand columns of table 2.12).

The price-induced reduction of elastic demands in ETEM-ED-SWI contributes to reduce the emissions by 2.5% and 9.6% in 2050 under S20 and S40 respectively, in comparison with scenarios where energy demands are not elastic to their own price. The highest reduction of energy demand occurs in transportation, more particularly in aviation. In residential, demand reductions occur for electric appliances (up to 5% reduction), hot water (up to 3% reduction), and for the other end-use segments to a lesser extend (up to 1.5%). The price-induced reduction of energy demands reduces the resulting CO_2 tax computed by ETEM-ED-SWI by more than 50% at several periods.[15] In Figure 2.11, we

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[15] Given the effect of the price elasticity of energy demands, the estimation of the numerical values of elasticities deserves more attention in future work.

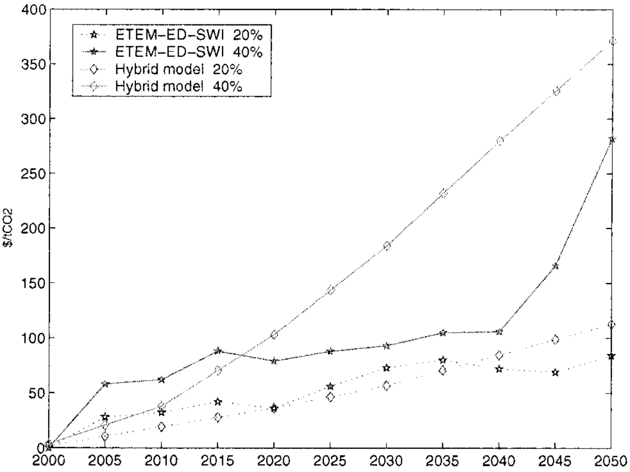

Figure 2.11. CO_2 Taxes under the 20% and 40% reductions targets in ETEM-ED-SWI and the Hybrid model

compare CO_2 taxes obtained from the hybrid model under S20 and S40 with the ones computed by ETEM-ED-SWI under the same conditions. The resulting CO_2 taxes appear to be higher in the short term in ETEM-ED-SWI than in GEMINI-E3, but lower in the long term.

7. Conclusion

In the battery of models developed for the assessment of climate policy, it is now considered "good practice" to use CGEMs to represent the macro-economic adjustments and ETEMs to detect efficient technology and energy-option choices. The question of how to connect together these two modelling tools in order to obtain a better assessment of climate policies is not yet fully answered. In this report we have presented a CGEM and an ETEM adapted to the analysis of the economics of climate in Switzerland. We have also presented a scenario built from the use of an hybrid model composed of modules borrowed from the CGEM and the ETEM. This experiment has illustrated a way to establish a useful dialogue between these two classes of models. More precisely:

- The introduction of the ETEM-RES model in GEMINI-E3 allows to take into account a more appropriate representation of energy consumption based on a precise technological representation of the energy system. It also preserves the consistency of the CGEM, i.e., general equilibrium interactions at the national and international levels.[16]

- This method allows an easy introduction of technological innovation in the energy fields and, consequently, permits the analysis of the implication of future energy technology on a carbon abatement strategy.
- The approach can also be used to test mixed or hybrid strategies combining tax instruments and standards-based regulation (i.e., policies and measures like efficiency standards on household equipment).

Some methodological aspects of this work need to be discussed. For example, the way we represent the price elasticity of useful energy demands in the residential sectors might be improved. As explained above, from the CGE model, one can only get a unique elasticity parameter based on aggregate consumption. One possibility would be to use an elastic version of ETEM, as developed in the world MARKAL model and following the approach proposed by Loulou and Lavigne (1996), and to implement only energy prices and carbon taxes obtained from the CGE model.

Other methodological aspects regarding the computation of MAC curves in the two models need to be considered. In a CGE model, marginal abatement costs reflect a change in terms of trade, and a domestic cost (deadweight loss) which can be broken down into two components (Bernard and Vielle, 2003). The first is a pure cost of carbon taxation, which is the integral below the curve of carbon tax. It is the domestic cost that would emerge without initial distortion in the economy. The second component is the additional cost (whether positive or negative) resulting from initial distortions in the economy (Babiker et al., 2003). Sectoral models can only estimate the pure cost of carbon taxation. In Bernard and Vielle (2003), it is shown that carbon tax curves obtained from a CGE model (GEMINI-E3) and a bottom-up model (POLES) may be close to each other. However, modeling results greatly differ when tax distortion effects are accounted for in the CGE. In this paper, we consider only the pure cost of carbon taxes. Other experiments are required to assess the impact of pre-existing energy taxation on technology choices in ETEM-SWI and welfare change.

Further developments are also envisioned to treat other sectors of the Swiss economy, like, e.g., transportation or electricity production, in a similar way. It would require to address the issue of making assumptions

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[16] On international markets of goods, and in particular the energy market.

on the future of nuclear production in Switzerland, and international trade in electricity. It would also imply to consider the uncertainty related to the availability and the costs of non-carbon backstop technologies such as electric vehicles, fuel cell cars, etc. Therefore, sensitivity analysis might be necessary.

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Chapter 3

MODERATED DECISION SUPPORT AND COUNTERMEASURE PLANNING FOR OFF-SITE EMERGENCY MANAGEMENT

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Valentin Bertsch
Otto Rentz

Abstract Emergency situations, both man-made and natural, can vary substantially, however, they do share the characteristic of sudden onset and the necessity for a coherent and effective emergency management. In the event of a nuclear or radiological accident in Europe, the real-time online decision support system RODOS provides support from the early phase through to the medium and long-term phases.

This paper describes the role of multi-criteria decision analysis (MCDA) in ensuring the transparency of decision processes within off-site emergency management. A moderated decision making workshop based on a hypothetical accident scenario focusing on the evaluation of long-term countermeasures using the RODOS system and MCDA methods is presented.

1. Introduction

Emergency situations, both man-made and natural, necessitate a coherent and effective emergency management involving complex decisions. Many conflicting objectives must be resolved, priorities must be set, and perhaps most importantly, the various perspectives of many stakeholder groups must be brought into some form of consensus. In order to ensure transparency during the decision making process multi-criteria decision analysis is vitally important (French and Geldermann, 2004; Keefer et al., 2004; Hämäläinen et al., 2000). In particular, the evaluation of long-term countermeasures after a nuclear or radiological accident requires operationally applicable multi-criteria methods and evaluation techniques to guide and support the decision makers during the decision making process.

In this chapter the focus is on decision problems in the context of environmental emergency management. Special attention is paid to the evaluation of long-term countermeasures (cf. Figure 3.1) after the occurence of a nuclear or radiological accident in Europe. A characterisation of the different phases of emergency management and corresponding countermeasures is shown in Figure 3.1. Emergency management in the early phase involves urgent decisions on short-term measures such as evacuation, sheltering or distribution of stable iodine. In the longer term, decisions on remediation strategies such as cleaning of streets, mowing of grass, removal of bushes, removal of street surfaces or relocation are required in order to bring back "normal life" to an affected region. One problematic aspect within the context of emergency management is that the teams of decision makers (DMs) that are confronted with the responsibility of handling emergency situations often are working together for the first time (French, 1995; Paton and Flin, 1999).

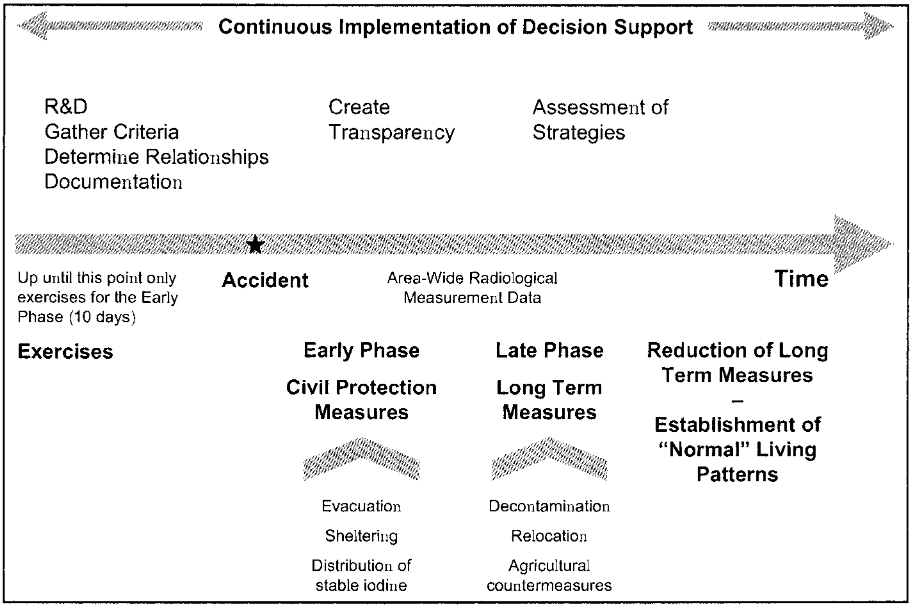

Figure 3.1. Implementation of decision support throughout all phases of emergency management

The European research project EVATECH[1] is aimed at improving decision support methods, models and processes in ways that take into account the expectations and concerns of different stakeholders participating in decision making that protects the public and workers in a nuclear emergency situation.

Within the EVATECH project decision making workshops have been organised in the participating countries in order to identify feasible clean-up actions in inhabited contaminated areas after a nuclear or radiological accident. The French-German Institute for Environmental Research (DFIU) of the University of Karlsruhe, Germany, and the Federal Office for Radiation Protection (BfS) in Freiburg, Germany, facilitated a workshop in Germany focusing on the evaluation of long-term countermeasures.

This chapter is structured as follows: Section 2 gives an introduction to the basic structure, components and features of the RODOS system.[2] Furthermore, this section deals with the multi-criteria based evaluation tool Web-HIPRE[3], which, when integrated into the RODOS system, ensures transparent and coherent decision support for countermeasure evaluation after a nuclear or radiological accident. A case study consisting of a hypothetical (radiological) accident scenario, possible countermeasures and clean-up actions is introduced in Section 3. The decision making workshop, its course of action and results are described in Section 4. Finally, Section 5 summarises the main results and indicates future research needs in this area.

2. Decision support systems for emergency management

The real-time on-line decision support system RODOS (cf. Section 2.1) is designed to provide consistent and comprehensive information in the event of a nuclear accident in Europe. Within the EVATECH project, the decision analytic software Web-HIPRE (cf. Section 2.2) has been integrated into RODOS in order to provide a transparent and coherent evaluation of alternative countermeasure strategies, whose potential benefits and disadvantages are quantified by the RODOS system.

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[1] EVATECH: Information Requirements and Countermeasure Evaluation Techniques in Nuclear Emergency Management — is carried out within the Fifth Framework Programme of the European Community. The project involves ten partner institutions in seven European countries. See: http://www3.sckcen.be/samen/public/index_EVATECH.html

[2] RODOS: Real-time On-line Decision Support system for nuclear emergency management.

[3] Web-HIPRE: HIerarchical PREference analysis in the World Wide Web (see: http://www.decisionarium.hut.fi and http://www.hipre.hut.fi) (Hämäläinen and Mustajoki, 1998; Mustajoki and Hämäläinen, 2000; Hämäläinen, 2003).

2.1 The RODOS system

The development of RODOS is a major item in the area of radiation protection of the European Commission's Framework Programmes. An important task is the prediction of the radiation exposure of the population during and after a nuclear event and the evaluation of possible countermeasure strategies (see: http://www.rodos.fzk.de). The main users of the system are those responsible for emergency management at the local, regional, national and supra-national levels.

RODOS is intended to supply support from the early phase through to medium-term and long-term countermeasures implemented weeks, months or years after an accident. Early countermeasures such as evacuation, shelter or distribution of stable iodine are usually limited to areas within a few tens of kilometers of the nuclear accident. Countermeasures of interest in the longer term are decontamination, restricted access measures (e.g., relocation) and the implementation of agricultural countermeasures.

Different views, competences, responsibilities and access rights of the users are reflected by three user categories. Detailed surveys of the development process, the underlying structure and the basic features of RODOS are given in Ehrhardt et al. (1993); French (2000), and French et al. (2000).

Models and data bases within RODOS contain extensive information about site and plant characteristics of the different nuclear power stations in Europe and the geographical, climatic and environmental variations. Its operational application requires on-line coupling to radiological and meteorological real-time measurements and meteorological forecasts from national weather services.

The modular structure (cf. Figure 3.2) is a key condition for extending or adapting the RODOS system. Two interfaces interconnect the independent modules:

- The "Message Interface," used for the exchange of messages between the different modules.
- The "Data Interface," allowing large amounts of data to be exchanged between the modules and the databases.

On the basis of the modular structure, the client server functionality enables RODOS to dynamically handle requests emerging during a decision making process. Any two modules can interact using the message and data interface, making one of them the "Server," providing a certain amount of services and the other the "Client," which asks for some specific service by sending requests and input data.

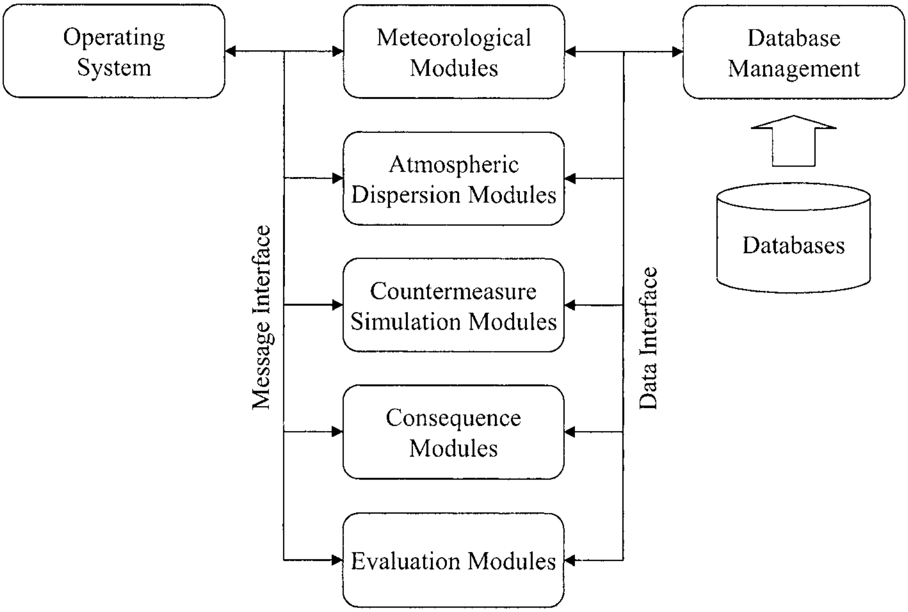
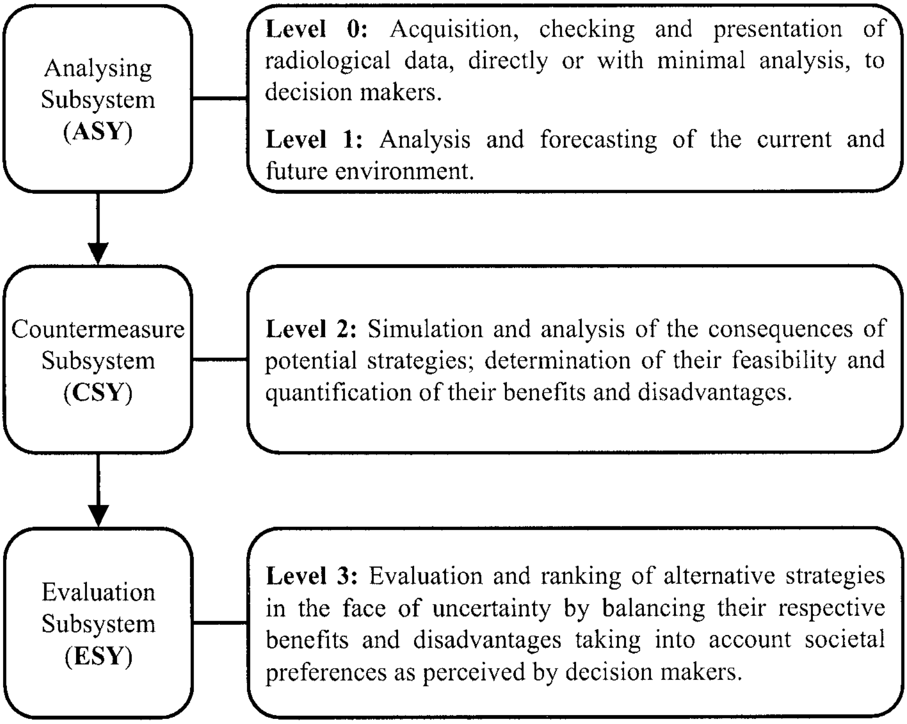


Figure 3.2. The modular structure of RODOS

Aside from the modular structure and the client server functionality which can be seen as key principles from an informatics point of view, RODOS is characterised by its conceptual architecture which consists of the following three subsystems (French, 2000):

- Analysing Subsystem (ASY) modules process incoming data and forecast the location and quantity of contamination including temporal variation.
- Countermeasure Subsystem (CSY) modules suggest possible countermeasures, check them for feasibility, and calculate their expected benefit in terms of a number of attributes.
- Evaluation Subsystem (ESY) modules rank countermeasure strategies according to their potential benefit and preference weights provided by the decision makers.

According to French (2000), RODOS acknowledges four levels of decision support (where support at higher levels includes that provided at lower levels) which can be related to its subsystem structure. This is illustrated in Figure 3.3. While support at levels 0, 1 and 2 is basically comprised of providing information to the DMs, support at level 3 is different in that it involves the use of evaluation techniques and thus seeks to model the DMs' judgements and preferences (French, 2000; Pa-



Level 0: Acquisition, checking and presentation of radiological data, directly or with minimal analysis, to decision makers.

Level 1: Analysis and forecasting of the current and future environment.

Level 2: Simulation and analysis of the consequences of potential strategies; determination of their feasibility and quantification of their benefits and disadvantages.

Level 3: Evaluation and ranking of alternative strategies in the face of uncertainty by balancing their respective benefits and disadvantages taking into account societal preferences as perceived by decision makers.

Figure 3.3. Levels of decision support related to the three subsystems of RODOS

pamichail and French, 2004). As mentioned previously, this chapter places special emphasis on decision support at level 3 and on the use of evaluation tools such as Web-HIPRE (cf. Section 2.2) to support a moderated workshop (cf. Section 4) (Mustajoki et al., 2004).

2.2 Web-HIPRE

Decision making in emergency management involves resolving many conflicting objectives, setting priorities, and perhaps most importantly, bringing the various perspectives of many stakeholder groups into some form of consensus (Sinkko, 2004). In order to ensure transparency during the decision making process multi-criteria decision analysis (MCDA) is vitally important as the following characteristics of MCDA point out (Belton and Stewart, 2002):

- The MCDA process helps to structure the problem.
- The models used provide a focus and language for discussion.
- The principal aim is to help decision makers (DMs) learn about the problem situation, about their own and others' value judgements,

and through organisation, synthesis and appropriate presentation of information to guide them in identifying, often through extensive discussion, a preferred course of action.

- The analysis serves to complement and to challenge intuition, acting as a sounding board against which ideas can be tested, but it does not seek to replace intuitive judgement or experience.
- The process leads to more considered, justifiable and explainable decisions. Thus, the analysis provides an audit trail for a given decision.

There are many software packages available today offering support for decision analysis. Different packages seem to fit best with different decision making contexts (French and Xu, 2004; Guitouni and Martel, 1998). A modified version of the multi-criteria based evaluation software Web-HIPRE acts as ESY within RODOS to support the countermeasure evaluation after a nuclear or radiological accident. Web-HIPRE offers both MAVT and AHP elicitation methods for decision support (Salo and Hämäläinen, 1997; French and Xu, 2004). Furthermore, it provides the possibility of illustrating the composite priorities and performing a sensitivity analysis.

3. Countermeasure strategies in an exemplar case study

The following fictitious radiological accident scenario forms the basis of the case study for the moderated decision making workshop described in Section 4.

3.1 The hypothetical accident scenario

The fictitious contamination situation in the scenario was caused by a radioactive emission (isotopes J-131, Ba-140, Cs-137) from a nuclear power plant. The city primarily affected has a population of 28000. A short rain shower caused a very high local urban contamination — more than ten times higher compared to the surrounding area. The radioactive cloud then moved on due to instable meteorological conditions and contaminated an agricultural area of approximately 5000 km^2. Figure 3.4 shows the location of the considered nuclear power plant and the city primarily affected. Moreover, the figure visualises the geographical contamination situation in the surrounding area of the power plant.

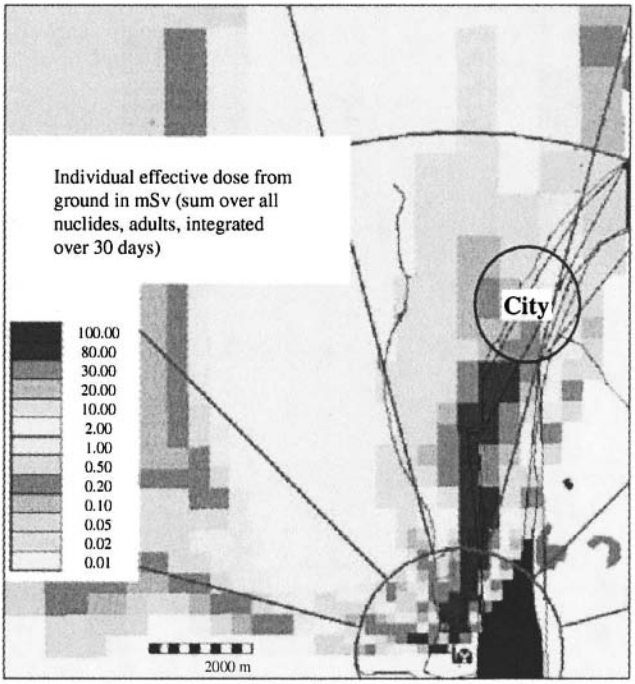


Figure 3.4. Contamination of surrounding area of the power plant

3.2 Immediate Countermeasures recommended to the general public

According to the hypothetical scenario, the inhabitants of the city primarily affected were successfully evacuated and all other catastrophe protection measures were carried out as planned before the release of the radioactive cloud. Uptake of stable iodine was advised for children. After the passing of the radioactive cloud most of the inhabitants could return to their homes — except for those from areas A and B, in which forecasts (or measurements) suggested that the limit of 30mSv for effective ground dose within 30 days was exceeded. Table 3.1 shows the definitions of the different areas which were selected according to the radioactive dose and in addition contains their size and population. It is assumed that measuring teams can enter the area and that measurements carried out thus far are identical to the forecasts of RODOS.

3.3 Clean-up actions

The consideration of area A is omitted within this case study since a permanent relocation of the inhabitants is necessary due to the high

Table 3.1. Areas, size and population

	Dose	Size [km^2]	Population
Area A	1 year > 100 mSv	0.32	60
Area B	30 days > 30 mSv	0.32	395
Area C	30 days > 20 mSv	1.76	2168
Area D	30 days > 10 mSv	7.52	9265

Table 3.2. Strategies and respective measure combinations

Strategy	Area B	Area C	Area D
S 1	no measures	no measures	no measures
S 2	30 additional days evacuation & cleaning of streets	no measures	no measures
S 3	7 additional days evacuation & cleaning of streets	cleaning of streets	cleaning of streets
S 4	14 additional days evacuation & cleaning of streets & mowing of grass & removal of bushes and shrubs	cleaning of streets & mowing of grass & removal of bushes and shrubs	mowing of grass & removal of bushes and shrubs
S 5	30 additional days evacuation & cleaning of streets & mowing of grass	cleaning of streets	cleaning of streets
S 6	14 additional days evacuation & cleaning of streets & mowing of grass & removal of bushes and shrubs	cleaning of streets & mowing of grass & removal of bushes and shrubs	cleaning of streets & mowing of grass & removal of bushes and shrubs
S 7	14 additional days evacuation & mowing of grass & removal of bushes and shrubs & removal of street surfaces	mowing of grass & removal of bushes and shrubs & removal of street surfaces	mowing of grass & removal of bushes and shrubs & removal of street surfaces

contamination. Thus, the discussion about clean-up actions is reduced to decisions about the implementation of measures in areas B, C and D. Moreover, the question of when the inhabitants of area B can return to their homes is of interest.

Table 3.3. Decision table

	S 1	S 2	S 3	S 4	S 5	S 6	S 7
Waste (tons)	0	40	26235	35705	4594	35948	1801140
Work (man hours)	0	1000	33896	37392	12560	43472	110352
Costs (million €)	0	3	2	3	4	3	249
Avoided collective dose (manSv)	0	84	452	1116	566	1336	1695
Avoided individual dose - area B (mSv)	0	87	69	177	187	177	219
Avoided individual dose - area C (mSv)	0	0	42	117	42	117	142
Avoided individual dose - area D (mSv)	0	0	19	42	19	61	80

Seven potential countermeasure strategies, i.e., measure combinations from individual measures according to the catalogue of provisions for areas B, C and D, are compiled in Table 3.2. The measures and their respective benefits and disadvantages result from the RODOS system. The reasonable combination of individual measures in the face of feasibility and public acceptability is an important topic within the moderated workshop (cf. Section 4). This means that it does not make sense to consider all possible measure combinations for the three areas under investigation, not only because the resulting number of strategies would be very high, but also because measure combinations such as "let inhabitants of area B return to their homes" and "additional evacuation of inhabitants of areas C and D" are not feasible.

The consequences (quantification of the respective benefits in terms of dose reduction, waste, work effort and costs) which result from the different strategies defined in Table 3.2 are shown in Table 3.3. These are the underlying values of the decision analysis (cf. Section 4.2) within the workshop.

4. The moderated workshop

Decisions in the context of emergency management involve many parties who have different views and responsibilities (Carter, 2004; French and Geldermann, 2004; Hämäläinen et al., 2000; Sinkko, 2004). Decision makers (DMs) are those responsible for the decision. Stakeholders share, or perceive that they share, the impacts arising from a decision and therefore they claim that their perceptions should be taken into account. Experts provide economic, engineering, scientific, environmental and other professional advice. Analysts (recently also seen as "facilitators," Belton and Stewart, 2002) are concerned with the synthesis of the DMs' and stakeholders' value judgements and the experts' advice. In addition, they guide and assist the DMs and know how to operate the MCDA algorithms (Geldermann and Rentz, 2004).

The French-German Institute for Environmental Research (DFIU) of the University of Karlsruhe, Germany, and the Federal Office for Radiation Protection (BfS) in Freiburg, Germany, organised a moderated workshop on "Decision analysis of clean-up actions in inhabited areas after an accidental release of radionuclides" in Germany based on the case study introduced in Section 3. There were 19 participants, including officials and politicians of regional, state and federal authorities, who represented the different stakeholder and expert groups in emergency management in Germany.

The identification of responsibilities and authorities is vital to implementing a rapid response in emergency management. Thus, scenario-focused workshops involving key stakeholders are conducted as emergency exercises using "moderation" methods (Seifert, 2002; French and Geldermann, 2004; Sinkko et al., 2004). The moderator acts as the leader of the discussion. His responsibility (as well as the facilitator's) is to manage the interactions with and between participants in decision teams and to choose instruments in order to foster the group's co-operation. The relation between the phases of moderation and those of multi-criteria decision analysis is visualised in Figure 3.5 (Geldermann and Rentz, 2004).

4.1 Course of action

In advance of the workshop, background material, an explanation of the introductory case study (cf. Section 3) and preparatory information for using the evaluation software Web-HIPRE were sent to the participants.

The RODOS system along with Excel was used to calculate the necessary data for the hypothetical accident scenario before and during the workshop. The main objectives of the workshops were:

- Exploration of information and data requirements for the decision makers.
- Verification of the factors driving decision making in the context of urban nuclear emergency management.
- Introduction to the evaluation software Web-HIPRE.

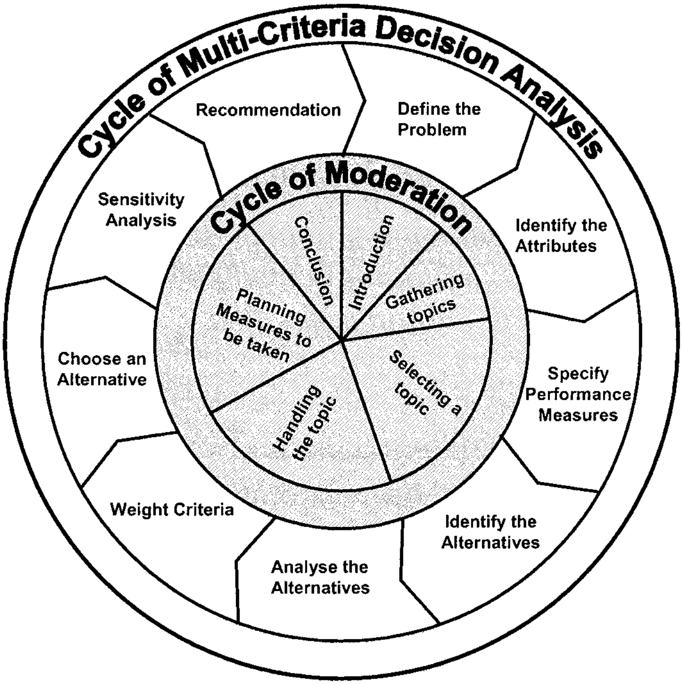


Figure 3.5. Steps of a moderation cycle and of multi-criteria decision analysis

- Development of methods for stakeholder involvement in exercises and emergency planning.

4.2 Decision analysis

The analysis and structuring of the case study was done in a moderated discussion. At the beginning, paperboard cards were used to collect important objectives. Further criteria (attributes) which were identified to be relevant by the experts and stakeholders on the regional, state and federal level were collected via card inquiry.

Collecting, structuring and assorting of information during the discussion provided deeper insight into the core of the problems under scrutiny and lead to some form of mutual understanding amongst all participants of the workshop.

The structuring and modelling process resulted in a decision tree (cf. Figure 3.6) which shows the "Overall goal" (e.g., "Radiation protection" or "Return to normal living") as the top criterion being split up into the subcriteria "Radiological dose," "Logistics" and "Costs," each of which can be split again. As a first step of the preference elicitation, the value

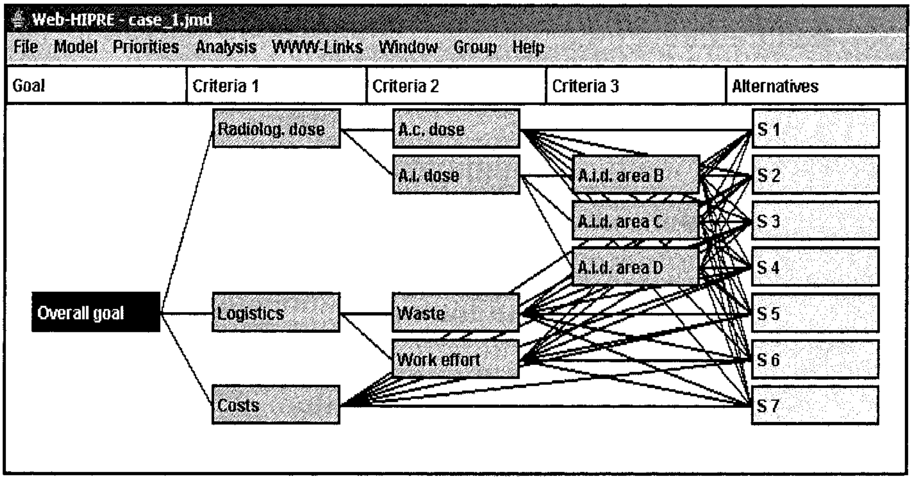


Figure 3.6. Decision tree for Table 3.3. The abbreviations "A.c. dose"/"A.i. dose" in the tree mean "Avoided collective dose"/"Avoided individual dose" respectively, "A.i.d." means "Avoided individual dose." The meaning of the strategies S 1 – S 7 is defined in Table 3.2.

functions and their shape were defined for each individual attribute using both linear and exponential functions. Subsequently, the weighting of the criteria of the decision tree were carried out. The following preference weights were elicited in a group discussion (cf. Figure 3.6):

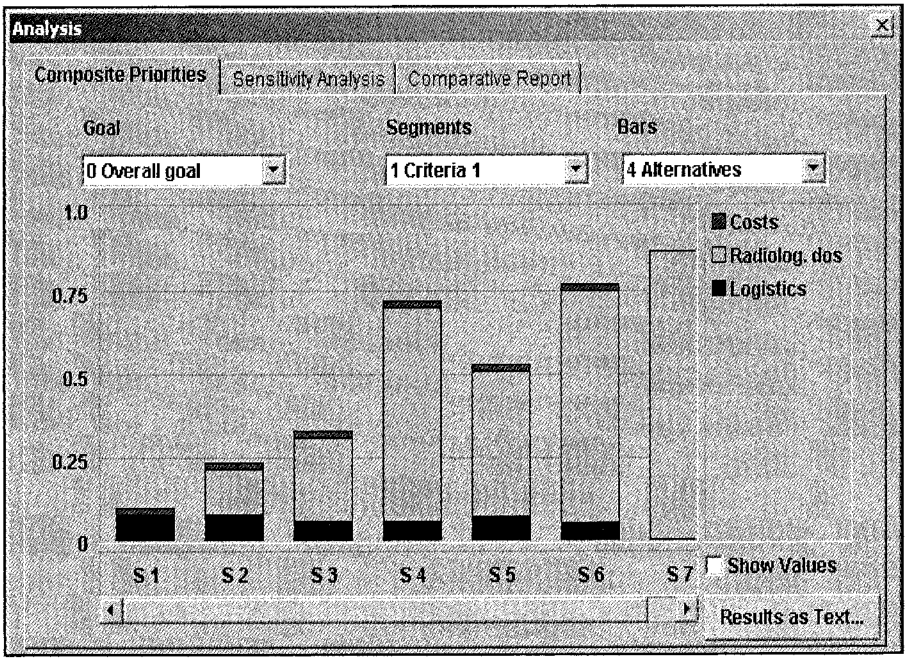
"Radiological dose" vs. "Logistics" vs. "Costs": Since decisions on the political level are made on what is humanly possible and not on costs, the weight for "Radiological dose" was much higher than the weights for "Logistics" and "Costs." The lowest weight was assigned to "Costs."

"Avoided collective dose" vs. "Avoided individual dose": Legal limiting values of dose are based on the individual in Germany. Thus, the weight assigned to "Avoided collective dose" is smaller than that assigned to "Avoided individual dose."

"Avoided individual dose in area B" vs. "Avoided individual dose in area C" vs. "Avoided individual dose in area D": As the radiation exposure decreases from area B to area D, the weights assigned to the corresponding attributes decrease in the same order.

"Waste" vs. "Work effort": The work safety of personnel is weighted more heavily than the problem of disposal of contaminated waste.

Since the aim of the workshop was the creation of awareness, only qualitative results are reported. After the completion of the weight



Goal: 0 Overall goal

Segments: 1 Criteria 1

Bars: 4 Alternatives

☐ Show Values

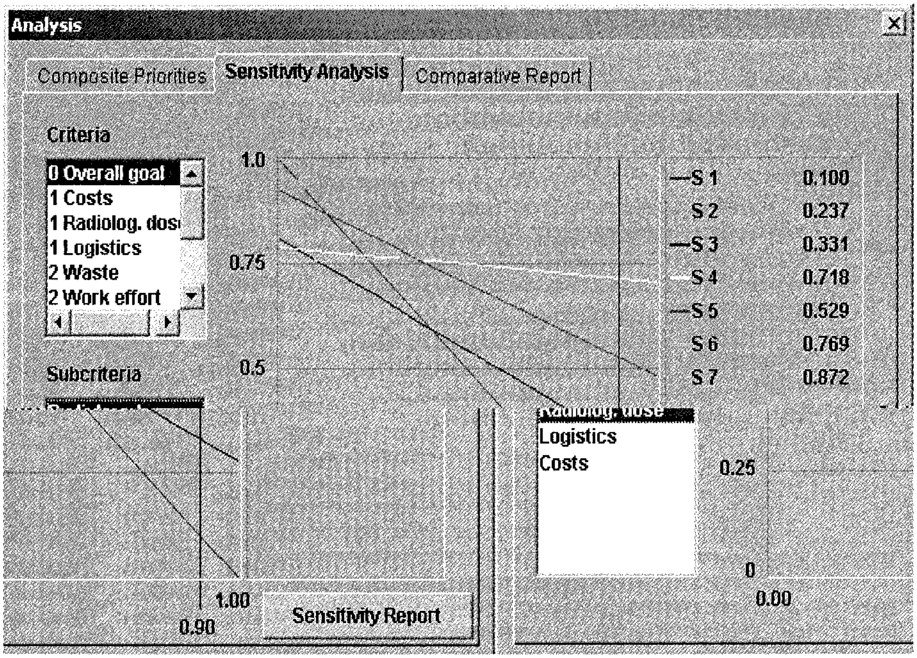
Figure 3.7. Results of decision analysis illustrated by Web-HIPRE

elicitation the question of whether a fixed decision tree, containing information about a fixed set of relevant decision criteria and feasible countermeasures identified by stakeholders and experts, was desirable or whether a decision tree should always by developed spontaneously in case of an emergency was raised for discussion.

4.3 Selected results

After all previously described steps have been carried out, Web-HIPRE showed strategy 7 to be the best alternative, followed by strategies 6 and 4 (cf. Figure 3.7). Furthermore, Figure 3.7 points out that “Radiological dose” is the most important factor driving the decision making process. As the weight assigned to “Costs” is very small, the large discrimination of the attribute “Costs” between strategy 7 and all other strategies (cf. Table 3.3) does not affect the results of the analysis.

Furthermore, it was determined that crucial evaluation differences exist if the individual dose based on 30 days or the collective dose based on one year were considered instead of the avoided dose values. In this case strategy 6 results in the best alternative, followed by strategy 5 and 4.



S 1	0.100
S 2	0.237
S 3	0.331
S 4	0.718
S 5	0.529
S 6	0.769
S 7	0.872

Figure 3.8. Sensitivity analysis in Web-HIPRE

This difference results from integration of the dose values over one year or alternatively 30 days and not over the average lifetime.

In addition, a sensitivity analysis on "Radiological dose" (cf. Figure 3.8) allows the examination of the robustness of the choice of an alternative relative to changes of the weight assigned to "Radiological dose." Moreover, the sensitivity analysis graph shows the range of weights for "Radiological dose" for which an alternative is the most preferred. Under the assumptions made above, the weight for "Radiological dose" can be changed by approximately 12 % without changing the optimality of strategy 7. For a further lowering of the weight, strategy 6 turns out to be the best alternative since the elaborate removal of the street surface in strategy 7 results in a high amount of waste, high work effort and exorbitant costs.

At the end of the workshop the participants were asked to fill in a questionnaire with statements about the suitability of decision making workshops for training and exercises for emergency situations. The general tendency of the responses was that the workshop was considered to be very useful for training purposes and that decision analysis helps to ensure the transparency of decisions and to understand the opinions and views of other participants.

5. Conclusions

Within the European research project EVATECH workshops on decision analysis for clean-up actions in the event of a nuclear emergency were arranged in Belgium, the UK, Denmark, Finland, Poland, Slovakia and Germany. The German workshop, as the first exercise on emergency response in urban areas in the late phase with extended participation by all levels of national authorities, was successful in determining issues for the further developments of methodology and decision support tools. The feedback from the participating stakeholders and experts was very positive. Multi-criteria decision analysis was considered to be a suitable framework for supporting and structuring decision processes within emergency management.

In order to improve the operational applicability of the RODOS system further developments of the multi-criteria based evaluation tool Web-HIPRE, integrated into RODOS as an evaluation subsystem (ESY), are necessary. Contributing to the direct involvement of the decision makers, an explanation module explaining the results of the decision analysis (Papamichail, 2000; Papamichail and French, 2003), is integrated into Web-HIPRE.

Since not all input parameters of a decision making model are clear-cut values, sensitivity analyses are important for the robustness of a decision. Furthermore, the evaluation of long-term countermeasures after an accident requires the involvement of advanced multi-criteria methods that take approaches for uncertainty modelling and sequential decision making into account.

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pared the case study and operated the RODOS system at the Federal Office for Radiation Protection (BfS) in Freiburg, Germany.

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Chapter 4

HYBRID ENERGY-ECONOMY MODELS AND ENDOGENOUS TECHNOLOGICAL CHANGE

Mark Jaccard

Abstract Energy-economy models are especially useful to policy makers if they indicate the effect of energy and environment policies on the technology choices of businesses and consumers - what is called endogenous modeling of technological change. The hybrid model described in this chapter is technologically explicit, like a bottom-up engineering model, but also behaviorally realistic, like a top-down macro-economic model. With this combination, it can simulate packages of policies that include economy-wide emissions charges and technology-specific regulations and subsidies. Recent improvement to the model involves estimation of its behavioral parameters from discrete choice surveys of business and consumer technology preferences.

1. The challenge of modeling endogenous technological change

1.1 The end state may not be expensive; getting there has its challenges

Consider three hypotheses:

- In this century, the global energy system can achieve near-zero emission energy while also reducing other impacts and risks, and more than doubling in size.
- In achieving this profound change, final energy prices will average no more than 25 – 50% higher in real terms than today.
- There will, however, be substantial transitional costs, some of which are real financial costs while others relate to the risk, time and quality preferences of businesses and consumers that economists include in the term welfare costs. These costs pose

a challenge for policy design and for the development of modeling tools that would assist the policy design process.

Compelling evidence for the first two hypotheses is available from recent surveys of the planet's available energy resources and their technological and economic potential. The World Energy Assessment produced for the United Nations Development Program (and the World Energy Council) in 2000 and the Third Assessment Report of the Intergovernmental Panel on Climate Change in 2001 provided substantial evidence that humanity could meet all its growing energy service needs at near-zero levels of the various emissions that currently affect interior air quality, urban air quality, acidity of regional precipitation and atmospheric concentrations of greenhouse gases (UNDP, 2000, IPCC, 2001). In addition to a substantial contribution from energy efficiency, several forms of renewable energy and nuclear power could satisfy global energy needs almost single-handedly.

Even fossil fuels, popularly thought to be rapidly depleting, could satisfy global energy needs for centuries at current use rates. Exhaustion of conventional crude oil and natural gas may mean little given the existing technical capacity to produce gaseous and liquid fuels (synthetic natural gas, synthetic gasoline, hydrogen, etc.) from any fossil fuel source including unconventional oil and gas, oil sands, orimulsion, and coal (and perhaps gas hydrates and deep geopressurized gas in future). Using conventional technologies, coal can be converted to electricity and hydrogen at wholesale, plant-gate product prices of 5 – 7¢/kilowatthour and \$8 – 10/gigajoule, including the costs of capturing and permanently storing carbon dioxide and other undesired byproducts. The cost of carbon control by this method is \$60 – 80/per tonne of CO_2 abated.

Evidence for the third hypothesis about high transitional costs has accumulated from three decades of policy efforts to influence energy use, initially from fears of impending oil shortages in the 1970s, then shifting to concerns about electricity investment risk in the 1980s, and then to a focus on energy-environment problems from the 1980s to the present. Throughout this period, governments, and quasi-governmental entities like utility commissions, tried to influence the direction of technological innovation and the diffusion of new technologies among businesses and consumers. They used subsidies, regulations, information programs and, in rare cases, financial penalties. It is generous to say that these efforts met with mixed success. While the magnitude of energy demand and the character of energy using technologies are undoubtedly different than they otherwise would have been, the energy system exhibited considerable inertia, and researchers increasingly focus on this. In essence, we have learned that while a more benign energy system is physically, technically and economically feasible, we have also learned how difficult it can be to turn the ship around. Our primary need is not more R&D to invent new technologies; we already know of alternatives that can achieve our objectives. Our critical need is to design policies that will foster the dissemination of these technologies by overcoming the substantial transitional costs associated with profound technological change, and to build models that help policy makers ascertain which approach is likely to be more effective in pursuit of this objective.

There are several reasons for these high transitional costs. They relate to the inertia of capital stocks as well as the healthy caution of those asked to acquire newer, possibly riskier technologies.

Units of capital stock, such as appliances, industrial equipment, vehicles and buildings, have different lifespans, determined in part by their physical endurance and in part by economic conditions. A piece of industrial machinery that might normally last 20 years could become economically obsolete after only five because of a new technology whose operating cost savings or incremental revenue gain offsets the extra capital cost of an early replacement. Normally, however, technological change is much less costly if it occurs at a pace consistent with the natural rate of capital stock turnover, which is especially related to physical endurance. But capital stocks are heterogeneous with respect to natural turnover rates — light bulbs can last less than a year while some buildings and infrastructure can last for centuries — and this poses a challenge for designing policies to induce technological change. An effective policy must simultaneously send a strong signal to support acquisition of a favored technology at the time of marginal change — that percentage of total stock that is new each year — without rendering uneconomic the rest of the existing stock of capital (Jacoby and Wing, 1999).

Other challenges relate to the fact that two technologies that apparently provide an identical service may actually differ in critical ways to businesses and consumers. Technologies may present different risks because of differences in newness or the time to pay back the investment, they may differ in the quality of service they provide, or their relative advantages may vary depending on the location or application (Pindyck, 1991, Stavins, 1999). The light bulb provides a mundane example.

New technologies usually have a higher chance of premature failure than conventional technologies and therefore pose greater financial risk. There is some probability that realized financial costs would exceed anticipated financial costs for new technologies. New compact fluorescent light bulbs have exhibited higher rates of premature failure than conventional incandescent light bulbs, requiring a higher-than-anticipated financial outlay because of early replacement in some cases.

Technologies with longer payback periods (relatively high up-front costs) are riskier if the cumulative probability of failure or accident, or undesired economic conditions, increases over time. Because of the higher purchase cost of compact fluorescent light bulbs, the chance of accidental breakage prior to paying back the initial investment is higher than for an incandescent light bulb.

Two technologies may appear to provide the same service to an engineer but not to the consumer. Many people find compact fluorescent light bulbs to be less than perfect substitutes for incandescent light bulbs in terms of attractiveness of the bulb, compatibility with fixtures, quality of light and time to reach full intensity, and would pay more to maintain high levels of these non-financial attributes.

Not all firms and households face identical financial costs: acquisition, installation, and operating costs can vary by location and type of facility. This heterogeneity means that a comparison of single-point estimates of financial costs of compact fluorescent light bulbs may exaggerate the total benefits of these relative to competitors.

These factors explain at a microeconomic level the high transitional costs to technological change. They are buttressed at a macro level of the economy by a complex of positive feedbacks between existing technologies, human preferences, economic structure and institutions that favor the current path over alternatives. Sometimes referred to as lock-in or path dependence, the forces that drive technological innovation and new product diffusion are biased in favor of the existing technological path, and this too implies high transitional costs to a substantial shift in direction (van den Burgh and Gowdy, 2000).

For path-altering technologies to compete, their chances are better if they are non-disruptive (or evolutionary), meaning that they mesh easily with the existing complex of technologies and institutions by exploiting niche opportunities within it. A hybrid gasoline-electric vehicle is non-disruptive in that it uses an internal combustion engine and the existing gasoline refueling infrastructure, yet it represents a significant shift from conventional vehicles. It can capture market share by targeting high-use niche markets like couriers and taxis, where its better energy efficiency is economically advantageous. A hydrogen fuel cell vehicle is disruptive (or revolutionary) in that it has a different engine platform and requires major investment in a hydrogen production and refueling infrastructure. Again, there may be niche opportunities, such as urban buses and other large vehicles, but these are more difficult and costly to develop by virtue of the disruptive nature of the technology.

1.2 Implications for policy design and policy modeling

While these transitional costs are formidable, there is much we can learn from past policy endeavors — successful and unsuccessful — to alter the pace and direction of technological change. There are several factors to consider.

There are ways to spread risk so that risk-averse businesses and consumers face less risk when acquiring a new technology. Automobile manufacturers have a long history of providing low-cost warranties for vehicles with new technological features, in effect sharing the higher risk among the purchasers of both the new technology and conventional vehicles. Given the higher expected cost to manufacturers of providing warranties for hybrid and eventually fuel cell vehicles, continuation of this practice would require that purchasers of conventional vehicles again share the risk, or that government cover the extra warranty cost, or some combination of these.

It is not easy to address the risks of longer payback because technology choices depend in part on the time preferences of businesses and consumers. However, all new technologies follow a learning curve in that capital and sometimes even operating costs decline with cumulative production (Grubler, 1998). The relationship is different from one technology to another, and is difficult to predict with accuracy, but falling capital costs reduce the payback period, which may increase the attractiveness of a given technology. With commercialization and increased diffusion, the costs of compact fluorescent light bulbs have fallen in some cases by over 50% in the last five years. Government policies to subsidize or even regulate technology diffusion can accelerate this positive feedback loop in which higher sales result in lower acquisition costs and lower costs result in higher sales.

Another feedback loop exists between the process of commercializing and diffusing new technologies and the value that businesses and consumers place on them. In some cases, only a few consumers will ever be interested in a particular technology. In other cases, more consumers will value the technology once they see its performance or hear about it from a growing number of family, friends and neighbors. Again, government policies can augment the positive feedback between the initial consumer response to a new technology, the subsequent experimentation by manufacturers to improve its attractiveness, and the growing sales that help to increase consumer awareness and receptivity (Norton, Costanza and Bishop, 1998). After many years with negligible consumer interest, compact fluorescent light bulbs have gained market share in recent years as manufacturers and electric utilities have worked to improve the appearance and performance of this technology and to increase consumer awareness.

The cost information that issues from the commercialization and early diffusion of new technologies is useful for understanding and addressing these transitional costs, but also for assessing the long-run economic trade-offs of adopting cleaner technologies. Many new technologies that policy makers wish to foster for environmental reasons may never be financially competitive with conventional technologies as long as the latter can use the environment as a free waste receptacle. But policy makers do not know the magnitude of the economic trade-off of adopting the cleaner technologies until some degree of commercialization and diffusion has occurred. This uncertainty affects their choice of policy instrument, and even their willingness to act when an environmental problem is encountered for fear of imposing severe economic disruption. There is therefore a great value to policy makers to the information that accompanies technology commercialization and diffusion.

Unfortunately, some environmental advocates compound the challenge of assessing and addressing the economic trade-offs by arguing that an environmentally benign economy is free or even profitable, in effect countenancing mild policies such as information provision, voluntary programs and modest subsidies. Where substantial economic trade-offs are involved, such policies have proven to be largely ineffective, as they do not help new technologies attain critical thresholds of commercialization and diffusion (OECD, 1999, 2003).

Thus, where cleaner technologies have relatively high transitional costs, and imply not insignificant long-run economic trade-offs, policy makers would benefit from knowing more about how different types of policies might induce long-run technological change. More compulsory types of policies include regulations and financial instruments, or some combination of these. Command-and-control regulations can require that all market participants meet a specific technology or emission standard. Emission charges can apply economy-wide or to specific sectors. An emission cap and tradable permit system regulates an aggregate emission outcome but signals the incremental cost of achieving this via the permit price that emerges from the trading of permits. New types of niche market regulations specify that a particular technology (low emission vehicles in California and other states) or form of energy (renewable-generated electricity in about 20 US states and several other countries) must attain a given minimum market share by some future period, and leave it to producers to figure out how.

But policy makers need more than just ideas for policy design, they need tools to help them evaluate the contribution of alternative policies or policy packages to their environmental and other objectives. Models need to provide a realistic indication of how businesses and consumers will respond to policies to induce technological change for environmental benefit – what is referred to as endogenous modeling of technological change. This includes information on long-run cost differences and therefore economic trade-offs, but also on the transitional costs that hinder even the first steps.

2. Models for assessing policies to induce technological change

2.1 Conventional top-down and bottom-up models

Historically, policy makers have faced the dilemma of choosing between bottom-up or top-down models to assess their policies to influence energy-related technology choices (Jaccard et al., 2003a). Bottom-up analysis, applied frequently by engineers, physicists and environmental advocates, estimates how changes in energy efficiency, fuel, emission control equipment, and infrastructure might influence energy use and thus environmental impacts. Technologies that provide the same energy service are generally assumed to be perfect substitutes except for differences in their anticipated financial costs and emissions. When their financial costs in different time periods are converted into present value using a social discount rate, many emerging technologies available for abating various emissions appear to be profitable or just slightly more expensive relative to existing stocks of equipment and buildings. Bottom-up models often show, therefore, that environmental improvement from energy use can be profitable or low cost if these low-emission technologies were to achieve market dominance.

Many economists criticize this approach, however, for its assumption that a single, anticipated estimate of financial cost, using the social discount rate, indicates the full social cost of technological change. As noted above, new technologies present greater risks, as do the longer paybacks associated with investments like energy efficiency. And some low-cost, low-emission technologies are not perfect substitutes.[1] To the

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[1] Externality costs, such as pollution damages, should also be included in social cost estimates unless options are being compared in terms of their relative cost-effectiveness in achieving a particular externality reduction target. In the case of greenhouse gas emission abatement, therefore, estimated changes in damages from higher greenhouse gas concentrations in the

extent that they ignore some of these costs, bottom-up models may inadvertently suggest the wrong technological options for policy makers. Ironically, with their portrayal of consumers as financial cost minimizers, some bottom-up modelers may be more susceptible than economists to the critique of applying a simplistic, rational-economic-man view of the world.

The alternative, top-down analysis, usually applied by economists, estimates aggregate relationships between the relative costs and market shares of energy and other inputs to the economy, and links these to sectoral and total economic output in a broader equilibrium framework—full equilibrium models are referred to as computable general equilibrium models. Elasticities of substitution (ESUB) indicate the substitutability between any two pairs of aggregate inputs (capital, labor, energy, materials), and between the different forms of primary energy (coal, oil, natural gas, renewables) or secondary energy (electricity, processed natural gas, gasoline, diesel, methanol, ethanol, hydrogen) as their relative prices change. Another key parameter in top-down models, the autonomous energy efficiency index (AEEI), indicates the rate at which price-independent technological evolution improves energy productivity.

High parameter values for energy-related ESUB (a high degree of substitutability between energy and capital, and between different forms of energy) implies that technological change for environmental improvement can occur at relatively low-cost. If this parameter is estimated from real market data, as energy prices and consumption changed historically, it is assumed to reveal the actual preferences of consumers and businesses. With AEEI and ESUB estimated, economists then simulate the economy's response to a financial signal (an emission tax, an emission permit price) that increases the relative cost of emission-intensive technologies and energy forms. The magnitude of the financial signal necessary to achieve a given emission reduction target indicates its implicit cost, including the intangible costs related to the risks of new technologies, the risks of long payback technologies, and preferences for the attributes of one technology over its competitor. Thus top-down cost estimates are usually higher and almost never lower than bottom-up estimates to the extent that they include all of these transitional and long-run costs of technological change. However, estimation of top-down parameters from real market data is a substantial challenge because there is often insufficient variability in the historical record to enable statistically valid estimation of all parameters. Most computable general equi-

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atmosphere would not be included in social costs, but other externality benefits, such as a reduction of local air pollution damages, would be.

librium modelers set the key parameters of their models judgmentally, which can therefore result in both high and low cost estimates for environmental improvement depending on the ESUB values chosen (Bataille, 2004).

The top-down approach is also vulnerable to the criticism of being unhelpful to policy-makers. In the pursuit of substantial technological change for environmental objectives, policy-makers need to know the extent to which their policies might influence the characteristics and financial costs of future technologies, and the likely willingness of consumers and businesses to adopt these. If the critical top-down parameters for portraying technological change — ESUB and AEEI — are estimated from aggregate, historical data, there is no guarantee that these parameter values will remain valid into the future under different policies for environmental improvement (Grubb et al., 2002). For example, until recently, there was little incentive to design and commercialize technologies with zero or near-zero greenhouse gas emissions. Today, such technologies are under development worldwide, providing households and firms with new choices. ESUB values in future may be different. AEEI may also evolve differently. As this process unfolds, the estimated cost of greenhouse gas abatement may decrease, but top-down models are unable to help policy makers assess this dynamic. Increasingly concerned with this problem, some top-down modelers are exploring ways of treating technological change endogenously. However, as of yet there has been little success in linking real-world evidence to the estimation of aggregate parameters of technological change in these models (Loschel, 2002).

Another difficulty is that the constraints of policy development processes often push policy-makers towards technology- and building-specific policies in the form of tax credits, subsidies, regulations and information programs. This is especially the case where emission charges would need to be high in order to overcome high transitional costs of environmental improvement, as such a prospect leads policy-makers to apply a mix of more focused policies in order to minimize the public reaction that significant energy price increases might trigger. Because conventional top-down models represent technological change as an abstract, aggregate phenomenon — characterized by ESUB and AEEI parameter values — this approach only helps policy-makers assess economy-wide policy instruments such as taxes and tradable permits. A model would be more useful if it could assess the combined effect of these economy-wide, price-based policies with the technology-focused policies, but this requires the explicit representation of individual technologies that top-down models lack.

2.2 Criteria for modeling endogenous technological change

Box (1979) noted that, "all models are wrong, but some are more useful." While it is impossible for any policy model to be completely accurate in its representation of current conditions or its characterization of future dynamics, the above discussion suggests criteria by which we can judge the ability of a model to be more useful to policy makers seeking to induce technological change. Policy makers need models that can evaluate the combined effect of policies that range from economy-wide to technology-specific, and these instruments will likely include command-and-control regulations as well as financial charges and subsidies. In doing this, the models need to satisfy at least three criteria: technological explicitness, behavioral realism and equilibrium feedbacks between energy-technology decisions and the overall structure and performance of the economy. Figure 4.1 portrays these three dimensions, showing a conventional bottom-up model, a conventional top-down model, and the hybrid alternative model, called CIMS, that I describe in Section 3.[2]

Conventional bottom-up models do well in terms of technological explicitness, but less well in terms of the other two attributes. There are, however, some types of bottom-up models that also perform fairly well in terms of equilibrium feedback by integrating energy supply and demand, and in a few cases by including interactions between this integrated energy system and the economy as a whole. Developments with the MARKAL optimization model have been particularly noteworthy (Nystrom and Wene, 1999). New variants of this model (one called SAGE) have also involved efforts to introduce some degree of behavioral realism into the technology acquisition process.

Conventional top-down models can perform well in terms of equilibrium feedback and perhaps in terms of consumer and business preferences, although the latter depends on the empirical validity of their portrayal of behavior. But their lack of technological explicitness impedes their ability to portray the dynamics of technological change in anything but the most rudimentary manner. This is especially a liability when assessing the potential for overcoming transitional costs through cumulative production of new technologies on the one hand and assessing the shifts in preferences that may occur with greater market penetration of these on the other (DeCanio, 2003). A few top-down models have attempted to incorporate some technological explicitness, but thus far this

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[2] CIMS was originally the acronym for the Canadian Integrated Modeling System but as the model is now applied to other countries, the acronym is treated as a proper name.

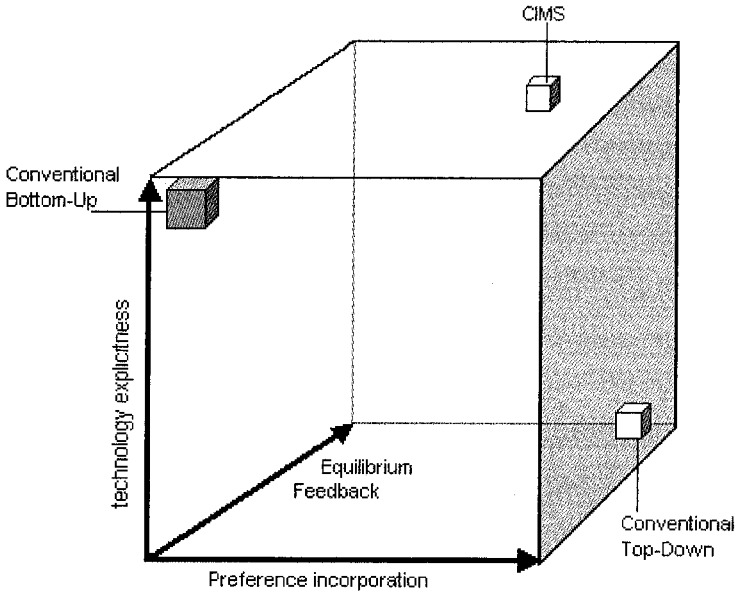

Figure 4.1. Criteria for assessing energy-economy models

has been limited to the energy supply sector and usually just electricity generation.

To be particularly useful, a policy model would perform fairly well in terms of all three criteria. It would be technologically explicit, including an assessment of how policies to promote technology commercialization and diffusion might affect the future financial costs of acquiring new technologies. It would be behaviorally realistic, including an assessment of how policies to increase market share might affect the future intangible costs of acquiring new technologies. It would have equilibrium feedbacks linking energy supply and demand, and both of these with the evolution of the structural and total output of the economy. This equilibrium dimension might include feedbacks between countries in cases where the environmental challenge is one that requires a global effort, such as with greenhouse gas abatement.[3]

Because neither the conventional top-down nor bottom-up models have fully met these criteria for usefulness to policy makers, several

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[3] A more ambitious definition of equilibrium feedback includes the relationship between the energy-economy system and the climate. A new generation of integrated models takes this approach (Kolstad, 1998).

modelers have explored the development of hybrid models that are technologically explicit and behaviorally realistic, while also capturing the macroeconomic feedbacks between energy supply-demand adjustments and the rest of the economy. This research is still at an early stage, but portrayals of hybrid modeling of some kind include Jaccard et al. (1996), Bohringer (1998), Jacobsen (1998), Koopmans and te Velde (2001), Morris et al. (2002), and Frei et al. (2003). Most efforts at hybrid modeling involve the incorporation of some technological detail on the energy supply-side in what is otherwise a top-down, computable general equilibrium model. In the remainder of this paper, I describe the method and some applications of a hybrid model that has the full technological richness of a bottom-up model, but incorporates empirical estimation of parameters that allow for endogenous modeling of technological change.

3. A hybrid modeling approach: CIMS

3.1 Model structure and simulation of capital stock turnover

CIMS is an integrated, energy-economy equilibrium model that simulates the interaction of energy supply-demand and the macroeconomic performance of key sectors of the economy, including trade effects. Unlike most computable general equilibrium models, however, the current version of CIMS does not equilibrate government budgets and the markets for employment and investment. Also, its representation of the economy's inputs and outputs is skewed toward energy supply, energy intensive industries, and key energy end-uses in the residential, commercial/institutional and transportation sectors.

As a technology vintage model, CIMS tracks the evolution of capital stocks over time through retirements, retrofits, and new purchases, in which consumers and businesses make sequential acquisitions with limited foresight (Jaccard et al., 2003a). The model calculates energy costs (and emissions) at each energy service demand node in the economy, such as heated commercial floor space or person-kilometer-traveled. In each time period, capital stocks are retired according to an age-dependent function (although retrofit of unretired stocks is possible if warranted by changing economic conditions), and demand for new stocks grows or declines depending on the initial exogenous forecast of economic output, and then the subsequent interplay of energy supply-demand with the macroeconomic module. A model simulation iterates between energy supply-demand and the macroeconomic module until energy price changes fall below a threshold value, and repeats this convergence procedure in each subsequent five-year period of a complete run, which usually extends 3 – 35 years.

CIMS simulates the competition of technologies at each energy service node in the economy based on a comparison of their life cycle cost (LCC) and some technology-specific controls, such as a maximum market share limit in the cases where a technology is constrained by physical, technical or regulatory means from capturing all of a market. Instead of basing its simulation of technology choices only on financial costs and social discount rates, CIMS applies a definition of LCC that differs from that of bottom-up analysis by including intangible costs that reflect consumer and business preferences and the implicit discount rates revealed by real-world technology acquisition behavior. Equation (4.1) presents how CIMS determines technology market shares for new capital stocks.

$$\mathrm{MS}_j = \frac{[\mathrm{CC}_j * r/((1-1+r)^{-n}) + \mathrm{OC}_j + \mathrm{EC}_j + i_j]^{-v}}{\sum_{k=1}^{K}[\mathrm{CC}_k * r/((1-1+r)^{-n}) + \mathrm{OC}_k + \mathrm{EC}_k + i_k]^{-v}} \tag{4.1}$$

MS_j is the market share of technology j, CC_j is its capital cost, n is technology lifespan, OC_j is its maintenance and operation cost, EC_j is its energy cost, which depends on energy prices and energy consumption per unit of energy service output — producing a tonne of steel, heating a m^2 of a residence, transporting a person one kilometer. The r parameter represents the weighted average time preference of decision makers for a given energy service demand; it is the same for all technologies at a given energy service node, but can differ between nodes according to empirical evidence. The i_j parameter represents all intangible costs and benefits that consumers and businesses perceive, additional to the simple financial cost values used in most bottom-up analyses, for technology j as compared to all other technologies k at a given energy service node.

The v parameter represents the heterogeneity in the market, whereby different consumers and businesses experience different LCCs, perhaps as a result of divergent preferences or as a result of real financial costs being different for different customers. It determines the shape of the inverse power function that allocates market share to technology j. A high value of v means that the technology with the lowest LCC captures almost the entire new market share (Figure 4.2). A low value for v means that the market shares of new equipment are distributed fairly evenly, even if their LCCs differ significantly. At $v = 10$, when technology A becomes 15% more expensive than B, B captures 85% of the market. At $v = 1$, when technology A becomes 15% more expensive than technology B, B only captures 55% of the market. We consider this second case a more heterogeneous market, and the first case a more homogeneous market. A traditional linear programming optimization model would have $v =$

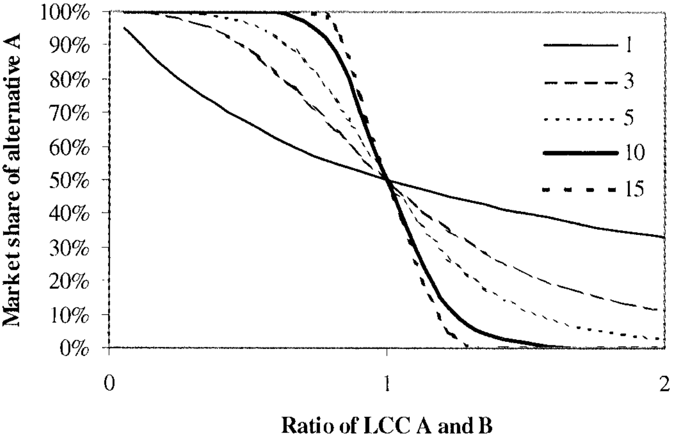

Figure 4.2. Market heterogeneity in the CIMS model

∞, equivalent to a step function where the cheapest technology captures 100% of the market — a completely homogeneous market.

Thus, CIMS is technologically explicit and behaviorally realistic. It also incorporates substantial feedbacks, although not yet to the full extent of most computable general equilibrium models. These characteristics explain the positioning of CIMS in Figure 4.1.

3.2 Empirical basis of parameter values

Key parameters in CIMS are technological and behavioral. Estimation of technological parameters requires little explanation. Technical and market literature provide the conventional bottom-up data on the costs and energy efficiency of new technologies. Because there are few detailed surveys of the annual energy consumption of the individual capital stocks tracked by the model (especially smaller units), these must be estimated from surveys at different levels of technological detail and by calibrating the model's simulated energy consumption to real-world aggregate data for a base year. The goal is to ensure that the energy use simulated by the model is within 5% of real-world energy use at whatever level of disaggregation these data are available. Sometimes the model is calibrated by simulation over a historical time period, tracking for example the change in vehicle fuel use with the rising share of sport utility vehicles as a check on detailed data.

Estimation of behavioral parameters is more complicated. In previous applications of CIMS, the three key behavioral parameters — i, r and v — were estimated through a combination of literature review, judgment, and meta-analysis. However, the available literature usually provides only separate estimates for the three parameters, often using the discount rate to account for several factors, such as time preference and risk aversion to new technologies. This creates problems for predicting the costs and effects of policies that focus on only one of these factors.

More recent estimation of these three behavioral parameters involves the use of discrete choice surveys for estimating models whose parameters can be transposed into the i, r and v parameters in CIMS (Rivers and Jaccard, 2004). The data for a discrete choice model can be acquired from the revealed preferences in actual market transactions or from the stated preferences in a discrete choice survey. In the latter case, a sample of consumers or business managers are presented with hypothetical choice sets and asked to choose the alternative that they prefer the most.

CIMS is made up of over 1,000 technologies competing for market share at hundreds of nodes throughout the economy. Obviously, gathering information on consumer and firm choices at each of these nodes is a huge task, so recent discrete choice research has focused on several critical nodes for policies to influence energy-related technology choices in the energy supply, residential, transportation and industrial sectors. Evidence from this research is used to inform the setting of parameters at other decision nodes.

The recent use of discrete choice research for CIMS has focused on stated preference surveys. There are several reasons for this choice. First, the explanatory variables in revealed preference data are often highly collinear and exhibit little variability in the marketplace, which can make estimating a model based on this kind of data difficult. Second, revealed preference data may have less plausibility in analyzing the impact of policies designed to move the economic system beyond its current technological context. Third, revealed preference data are often difficult to gather due to problems with respondent recollection of purchases and decisions made years in the past. Stated preference experiments are designed by the analyst and so avoid most of these problems. However, stated preference data can be biased because when answering a survey, consumers do not face real-world budgetary or information constraints. Also, biases may arise if consumers do not understand the survey properly or if they answer strategically to alter the survey results (Louviere et al., 2000, Train, 2002). Research has found, for example, that consumers often demonstrate a higher affinity for energy-efficient technologies, such as fuel-efficient vehicles, on stated preference surveys than they do in reality (Urban et al., 1996). Therefore, while stated preference surveys are likely to continue to dominate parameter estimation where dramatically new technologies are involved, there is an interest in combining this with some revealed preference research where feasible.

The discrete choice model is a linear-in-parameters utility function, as in Equation (4.2).

$$U_j = \beta_j + \sum_{k=1}^{K} \beta_k x_j k + e_j \tag{4.2}$$

U_j is the utility of technology j, β_j is the alternative specific constant, β_k is a vector of coefficients representing the importance of attribute k, x_{jk} is a vector of the k attributes of technology j, and e_j is the unobservable error term. In its generic form for discrete choice surveys, Equation (4.2) can be represented as Equation (4.3), where OC is non-energy operating cost, EC is energy cost, and OTHER is non-financial preferences.

$$U_j = \beta_j + \beta_{\mathrm{CC}}\mathrm{CC} + \beta_{\mathrm{OC}}\mathrm{OC} + \beta_{\mathrm{EC}}\mathrm{EC} + \beta_{\mathrm{OTHER}}\mathrm{OTHER} + e_j. \tag{4.3}$$

By assuming that the unobserved error terms (e_j) are independent and identically distributed Type 1 Extreme Value, it is possible to generate a model of the probability of a firm choosing technology j from the available set of technologies, K. This is called the multinomial logit model (Train, 2002), as shown in Equation (4.4), where U_j' is simply the observable portion of utility, and $U_j' = U_j - e_j$.[4]

$$\Pr(j) = \frac{e^{U_j}}{\sum_{k=1}^{K} e^{U_k}}. \tag{4.4}$$

A maximum likelihood routine is then used to find the β parameters that most closely match the left hand side to the right hand side of equation (4.4) for the set of observations. This produces the set of parameters for the discrete choice model that best matches the actual choices respondents indicated in their survey answers.

The estimated parameters of the discrete choice model can be used to provide estimates for the three key CIMS behavioral parameters (Rivers and Jaccard, 2004). The weighted average implicit discount rate applied by decision makers at a node can be determined by the ratio of the capital cost parameter to the annual cost parameters, as long as the capital stock lifespan is expected to be greater than about 15 years (Train, 1985; Train, 2002).[5] In Equation (4.5), β_{AC} is a parameter weighting all annual costs

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[4] Discrete choice literature usually denotes the observable portion of utility as V_j. It is presented as U_j' here to avoid confusion with the CIMS' v parameter.

[5] For short-lived technologies r is replaced by the formula for the capital recovery factor in Equation (4.1).

parameters together — the non-energy and energy operating costs in the case of Equation (4.3).

$$r = \frac{\beta_{\mathrm{CC}}}{\beta_{\mathrm{AC}}}. \tag{4.5}$$

Similarly, the (annual) intangible cost parameter can be calculated by comparing non-cost parameters to the parameter weighting the annual cost parameters. This parameter shows the annual monetary estimate of the intangible (non-financial) qualities of a given technology. For example, on average, consumers might be willing to pay \$400/year extra to drive a car, and avoid the (real or perceived) discomfort of riding a bus. If required in CIMS, the annual cost can be converted to a single up-front cost for inclusion with the capital cost in the calculation of LCC.

$$i_j = \frac{\beta_j}{\beta_{\mathrm{AC}}}. \tag{4.6}$$

The final CIMS behavioral parameter (v), representing the degree of heterogeneity in the market, is roughly equivalent to the "scale" of the MNL model (Train, 2002). If the error terms (e_j) are comparable in magnitude to the parameter (β_j and $\beta_k * x_{jk}$) values, the model shows a more heterogeneous market where the error term plays a dominant role in predicting technology choices. Since the error term is not known, even where one technology appears to have a clear advantage over others, the presence of a large error term can lead to the other technologies capturing a significant portion of the market. In contrast, if the error terms are much smaller than the parameter values, the model shows a much more homogeneous market, where predictions of technology choices are strongly dependent on the relative attributes of the technologies. Unfortunately, although both the CIMS and discrete choice models (such as the multi-nomial logit model) show similar logistic curves of technology adoption, they are different enough that it is not possible to directly estimate the CIMS heterogeneity factor from the scale of the discrete choice model. It is possible, however, to use ordinary least squares to find the value of v for which predictions from CIMS are consistent with predictions from the multi-nomial logit model over a broad range of energy, capital cost and non-energy cost conditions.

From this combination of discrete choice surveys and literature review, the behavioral parameters in CIMS cover a range of values depending on the decision maker whose technology acquisition behavior is being simulated. In general, industry and electricity generation sectors have lower discount rates, lower and in some cases zero intangible values, and less market heterogeneity compared to household energy consumption, personal transportation and some commercial energy uses.

With its emphasis on technological richness, the behavioral focus in CIMS is on providing an empirical foundation for its simulation of future technology choices. This is the rationale behind the use of discrete choice surveys for estimating its key technology acquisition parameters, and especially the use of stated preference surveys that can reveal how consumers and firms will respond to technological options that may differ significantly in the future. However, for any model that seeks a greater degree of equilibrium feedback, this depiction at the microeconomic level explains only part of the adjustment that may occur to policies intending to induce technological change. A further adjustment may occur in the demands for final and intermediate goods and services as their relative costs change, leading to structural change in the economy and changes in total activity levels. A rising cost for domestic steel production may lead to a decrease in domestic demand and a declining competitive position for domestic producers relative to foreign producers in domestic and export markets. A rising cost for mobility in personal vehicles may lead to a decline in the demand for mobility as well as shifts to public transit.

To include these equilibrium feedback effects, the energy supply-demand component of CIMS interacts with its macroeconomic module via demand functions whose elasticities represent the long-run demand response to a change in the cost of providing a good or service. These Armington elasticities were econometrically estimated from historical data by Wirjanto (1999). They may or may not be valid in depicting the future response to changes in the costs of providing goods and services, but there is as yet no alternative empirical way of assessing how future demands might change as a result of production cost changes. One consolation in the face of this uncertainty is that most policies currently contemplated, even those focused on greenhouse gas emissions, do not result in enormous changes in the costs of providing most goods and services covered by the Armington elasticities, so past responses may provide a reliable basis for simulating future responses. In specific cases where a significant response is anticipated that is outside the range of historical experience, it may be desirable to judgmentally set these. An example would be the case where a carbon tax only in Canada increased the relative cost of Canada's chemical exports to the US outside of the historical cost differential.

3.3 Simulating endogenous technological change with CIMS

The discussion of the high transitional costs to technological change pointed out that new technologies exhibit high initial capital costs that decline with cumulative production, and that consumer suspicion and lack of information about new technologies decline with rising market share. These relationships are well known, but they are difficult to predict in advance. Some new technologies will see little decline in capital costs with cumulative production because of a physical or technical constraint. Some new technologies will never be accepted by more than a small percentage of consumers.

Nonetheless, these are critical uncertainties for policy makers. They need help in distinguishing transitional costs from long run economic trade-offs. They need to know what policies have the best chance, in a politically acceptable way, of pushing new technologies to commercialization levels where their financial costs fall enough to test the potential for wide-spread public adoption. A hybrid model provides a mechanism for their exploration because of its focus on both technologies and real-world behavior. CIMS includes two functions for simulating endogenous technological change.

CIMS has a declining capital cost function which links a technology's financial cost in future periods to its cumulative production, reflecting economies-of-learning (and perhaps economies-of-scale depending on the technology), as in Equation (4.7). In this formulation, $C(t)$ is the financial cost of a technology at time t, $N(t)$ is the cumulative production of a technology at time t, and PR is the progress ratio, defined as the percentage reduction in cost associated with a doubling in cumulative production of a technology. Researchers have found empirical evidence of this relationship, with PR values typically ranging from 75% to 95% depending on the maturity of the technology and any special characteristics such as scale, modularity, thermodynamic limits, and special material requirements (McDonald and Schrattenholzer, 2001, Argot and Epple, 1990, Neij, 1997).

$$C(t) = C(0)\left(\frac{N(t)}{N(0)}\right)^{\log_2(\mathrm{PR})} . \tag{4.7}$$

More recent versions of bottom-up models apply declining cost functions (Grubler et al., 1999), but still in a manner that portrays consumer choice as fixated on deterministic financial cost minimization to the exclusion of all else. Consumer and business acceptance of new technologies is equally important, but bottom-up models fail to provide information about this to policy makers because of their lack of a behavioral dimension.

CIMS has a declining intangible cost function which links the intangible costs of a technology in a given period with its market share in the previous period, reflecting improved availability of information and decreased perceptions of risk as new technologies become increasingly integrated into the wider economy. Attraction to a new technology can increase as its market share increases and information about its performance becomes more available (Banerjee, 1992, Arthur, 1989).[6] This function can be estimated from literature review, but a series of discrete choice surveys are currently underway to estimate how changes in key attributes (range, fuel availability) might affect its evolution over time. Intangible costs for technologies decline according to Equation (4.8), where $i(t)$ is the intangible cost of a technology at time t, MS_{t-1} is the market share of the technology at time $t-1$, and A and k are estimated parameters reflecting the rate of decline of the intangible cost in response to increases in the market share of the technology.

$$i(t) = \frac{i(0)}{1 + Ae^{k*\mathrm{MS}_{t-1}}} \tag{4.8}$$

4. Recent policy applications of the CIMS hybrid model

The focus of this paper is to present the rationale for hybrid modeling of endogenous technological change and to make this approach more concrete by describing the structure, functions and parameter estimation of a specific hybrid model. Some recent applications of this model illustrate its potential usefulness to policy makers.

4.1 The Canadian National Climate Change Process

In 1998, Canadian federal and provincial governments established the National Climate Change Process to cost options for achieving Canada's greenhouse gas (GHG) emission reduction commitment under the Kyoto Protocol (2010 emissions at 6% below 1990 levels). Consultative research groups were established to provide technical and economic information about key GHG reduction actions. This information was provided to

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[6] This application of CIMS has some similarities to what is referred to as agent-based modeling in that it establishes a basic set of assumptions about initial behavior and then simulates behavioral dynamics as key conditions change — financial cost of a new technology, proportion of neighbors, family and friends who have acquired it.

two technologically-explicit energy-economy models. CIMS was operated as a hybrid model with some adjustment of its default behavioral parameters to match the data and expert judgment provided by the research groups. The other model, MARKAL, provided an alternative integrated, bottom-up optimization model. Both models were required to de-activate their macroeconomic modules, instead passing their detailed sectoral results for investment and operating costs to a macroeconomic model that estimated the total effect on the Canadian economy. National cost estimates were then generated for several scenarios which differed in terms of (1) the allocation of the reductions among sectors, (2) the allocation of reductions between domestic actions and purchases of international credits, and (3) the comparison of a single, economy-wide policy instrument — such as an emissions cap with tradable permits — with a package of technology- and sector-specific policies (Analysis and Modelling Group, 2000).

The results reported here are from the scenario in which the Kyoto target is applied nationally, Canada achieves the target via domestic actions alone, and does so using some technology- and sector-specific policies in concert with an economy-wide emissions cap and tradable permit policy. The specific policies include subsidies, regulations, research and development, and information programs (demonstrations, labeling, audits). Efficiency standards are tightened for building shells, heating and cooling equipment, vehicles, appliances, lighting, and some industrial equipment. Land-use zoning and planning policies improve the prospects for districting heating, cogeneration, and integrated residential and commercial development that reduces travel requirements. Subsidies foster renewable electricity technologies, fuel cell applications, ethanol use by vehicles, public transit infrastructure, changes to agricultural and forestry practices, and development of carbon capture and storage. The economy-wide tradable permit policy is designed to minimize distributional impacts, meaning that permits are primarily allocated according to current emission levels, with some adjustments to reflect significant differences in the marginal costs of GHG reduction.

Under the business-as-usual scenario, emissions were expected to be about 25% higher than 1990 levels by 2010, implying a reduction from projected levels of more than 30% in just 10 years. This scale of reduction requires a dramatic market shift to low-GHG technologies, absorbing all opportunities offered by the natural turnover of capital stock and even forcing premature switching to alternative fuels in electricity generation and vehicles, and intensive retrofitting of building shells. Given the values of the behavioral parameters in a hybrid model, significant price changes are required to motivate the actions required during the tight 10-

year timeframe between 2000 and the Kyoto deadline of 2010. Thus, the CIMS hybrid simulation of this scenario suggests that a GHG tradable permit price of \$150/t CO_2e would result from the national emissions cap that is set to achieve domestically the Kyoto target.[7] This translates into substantial price increases for retail energy commodities — 50% for gasoline, 40 to 90% for natural gas, and 5 to 100% for electricity depending on whether electricity is regionally generated by fossil fuels or hydropower. In aggregate, about 40% of the GHG reduction results from increased energy efficiency while 30% results from fuel switching, this latter occurring especially in the electricity sector. The net costs of these adjustments translate into a reduction in cumulative economic growth of about 3%, the equivalent of a one-year recession between 2000 and 2010.

The different scenarios for the required level of domestic GHG reduction provided data for constructing an approximate GHG emission abatement curve for both the CIMS hybrid simulation and the bottom-up optimization analysis by MARKAL as shown in Figure 4.3 (Jaccard et al., 2003b). While the bottom-up curve in this figure was generated using MARKAL, it could equally have been produced from running CIMS in conventional bottom-up mode by setting r at the social discount rate throughout the model, i at zero for all technologies and v at an extremely high value for all decision nodes. Test simulations show, however, that a bottom-up application of CIMS will produce a slightly higher cost curve than MARKAL because CIMS does not replicate an optimization model's perfect foresight about future energy supply-demand conditions.

The two curves provide decision-makers with information on the role of alternative cost definitions in explaining divergent cost estimates. The hybrid curve indicates positive costs at relatively low levels of emission reduction (economically beneficial actions that were forced upon the CIMS model by the issue tables) while the bottom-up curve suggests that up to 60 MT of reduction provide net benefits and that even at 120 MT the total costs are offset by total benefits. These cost estimates were generated using the same anticipated financial costs and other characteristics of technological options, an identical macroeconomic forecast, and the same macroeconomic model to simulate economic feedbacks. Both simulations draw on similar actions, with the electricity and transportation sectors responsible for much of the GHG emission reduction. But the bottom-up application defines costs as only anticipated finan-

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[7] CO_2e stands for CO_2 equivalent, which converts all GHGs into units of CO_2 in terms of their greenhouse gas effect. All monetary values are in Canadian dollars at \$1 CDN = \$.65 US in 2000.

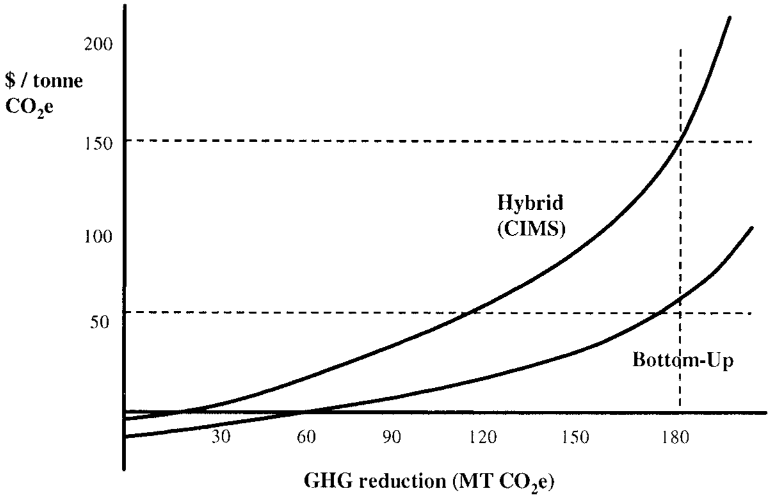

Figure 4.3. Canadian greenhouse gas abatement cost curves (2010)

cial costs (at the social discount rate) while the hybrid simulation defines costs as financial costs plus any intangible costs related to the risk aversion, time preference and quality preferences of businesses and consumers.

4.2 Simulating policies to induce long-run technological change

The application of a hybrid model to a near term target like GHG abatement in the Kyoto timeframe helps policy makers assess the extent to which the divergence in cost estimates is a result of behavioral assumptions. But a longer timeframe is required when the objective is to assess policies that seek to overcome the transitional costs to long-run technological change, and in turn to learn more about the likely long-run economic trade-offs in achieving environmental improvement.

A recent application of CIMS tested a small package of policies in Canada that would abate GHG emissions over a 35-year timeframe especially by inducing long-run technological change in rhythm with capital stock turnover (Jaccard et al., 2004). The policy package is dominated by market-oriented regulations that set an aggregate requirement in a sector or throughout several sectors by focusing on emissions or specific types of new technologies. The requirement is binding for the affected firms or individuals: participation in the program is compulsory, the target must be met, and penalties for non-compliance with the requirement are severe. Unlike traditional regulatory policies, however, a market-oriented regulation allows program participants to determine how they will meet their share of the aggregate requirement. Firms that find it cheap to meet the requirement may choose to exceed their individual targets and sell permits to firms who find the individual targets more challenging. In this way, emissions are reduced in an economically efficient manner — the cheapest opportunities are availed of first, with more expensive emissions reductions bypassed. A final characteristic of the market-oriented regulation package is a safety valve, which allows an unlimited number of permits to be purchased from the government at a predetermined price. This feature ensures that the total cost of the program will not be excessive if the economic trade-offs of environmental improvement turn out to be more expensive than expected.

The policy package included an emissions cap and tradable permit requirement applying to major industrial emitters including electricity generators in conjunction with several niche-market regulations stipulating minimum sales of low emission vehicles, minimum sales of renewable electricity and minimum carbon capture and storage from the fossil fuel industry. These more focused policies are designed to complement the broad emissions cap and tradable permit system by forcing the diffusion of innovative new technologies like wind and solar power or hybrid and hydrogen vehicles. Over time, as the niche-market regulations drive increased production of these innovative technologies, the effects of cumulative production and rising market share should reduce the transitional costs of technological change for environmental benefit. As this occurs, these policies can be phased out in favor of an economy-wide emission cap and tradable permit system or a GHG tax. But in its early phases, this policy approach provides a strong incentive for privately funded research, development, commercialization and diffusion of new technologies, without requiring politically unacceptable levels of production cost and energy-price increases.

Simulation using CIMS indicated that the policy package would achieve a significant reduction in GHG emissions in the Kyoto timeframe and, more importantly, stimulate substantial technological innovation and commercialization that would ensure continuing emission reductions in the post-Kyoto period, a time during which the international community expects to negotiate further commitments on global emission reduction. This is achieved without significant short-term economic disruption, either in terms of domestic energy prices or the international competitiveness of Canadian industry.

4.3 Generating ESUB and AEEI values for computable general equilibrium models

The earlier discussion of conventional top-down models noted their challenge in modeling endogenous technological change. If their critical parameters for technological change, ESUB and AEEI, are estimated from historical data, it is difficult to be confident that these values will apply to future conditions in which expectations and research focus have changed dramatically. Even top-down modelers who are concerned with this have no empirical means of estimating alternative future values for ESUB and AEEI when their models lack technological explicitness and behavioral realism at the technology level. By how much might the emergence of hybrid vehicles change the interfuel ESUB value related to personal transportation? By how much might carbon capture and storage change the interfuel ESUB value related to electricity generation, especially as GHG taxes rise?

With its detailed representation of how consumers and businesses might respond to new technologies and changing costs, a hybrid model can generate ESUB and AEEI values that reflect future technological conditions and shifting preferences of businesses and consumers, and these can be used to guide the setting of these parameters in top-down models that seek to portray endogenous technological change. In recent research, CIMS was applied to this end by price-shocking the model with a strongly contrasted range of energy prices (Bataille, 2004). The CIMS outputs (pseudo data) from this exercise can provide the standard inputs (changes in capital and individual forms of energy) used to estimate the parameters of production function models such as the Cobb-Douglas, the constant elasticity of substitution, and the translog. Used to estimate ESUB values with the translog production function, the CIMS pseudo data generated a long-run capital for energy ESUB value for Canada of 0.27 and interfuel ESUB values in the range of 0.8 – 2.0. The values differed widely between sectors, suggesting that structural change in future will also change ESUB values. A long-run simulation of CIMS with all prices held constant also produced an AEEI estimate of 0.4 – 0.6 depending on the sector. This compares to 0.25 – 0.5% for top-down estimates in the literature, and 0.75 – 1.5% for bottom-up estimates.

Current research with CIMS involves estimating how ESUB and AEEI values change as a result of the intensity of targeted niche market policies. This is being tested for applications of the model to the US, China, Canada and France in order to see how these values vary depending on the country.

5. Conclusions

Policy makers face a conundrum because of the considerable evidence that the human energy system can expand while dramatically reducing its impacts and risks, and yet maintain energy production costs that are not dramatically higher than today. But this implied shift is likely to face substantial transitional costs related to the high cost of new technologies and the healthy skepticism of those called upon to acquire these. To assess policies for overcoming these high transitional costs, policy makers need policy evaluation tools that combine technological explicitness with behavioral realism to show how actors in the economy will respond to alternative policies. These tools should also show how such microeconomic decisions would affect the overall macroeconomic evolution of the economy in terms of its structure and total output, as these will be important considerations in garnering policy acceptance.

The conventional top-down and bottom-up energy-economy models offered to policy makers are deficient in terms of at least one of these three attributes and thus are less useful than they could be. This explains the recent drive to design and apply hybrid models that are technologically explicit, behaviorally realistic and provide macro-economic equilibrium feedbacks to some extent. CIMS is a hybrid model that includes considerable progress along all three dimensions, but this creates its own challenges for the empirical estimation of its parameters, especially the behavioral parameters determining technology acquisition decisions. Recent work research with discrete choice surveys offers one promising approach for addressing this challenge.

The CIMS model is under active development, which includes its application to other countries, the inclusion of new technologies for producing hydrogen from fossil fuels with zero carbon emissions, and coordination with computable general equilibrium models. In the latter case, one avenue being pursued is to convert CIMS into a more complete computable general equilibrium model by adding macroeconomic functions for labor and capital markets, while another is to use pseudo data from simulations of CIMS to generate future ESUB and AEEI values for computable general equilibrium models that represent how these parameters might change in response to policies to induce technological change.

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Chapter 5

THE WORLD-MARKAL MODEL AND ITS APPLICATION TO COST-EFFECTIVENESS, PERMIT SHARING, AND COST-BENEFIT ANALYSES

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Abstract In this article, we present the new multiregional global MARKAL-TIMES[1] model and on several recent applications to global energy-environment issues. The development of the model was motivated by the need to analyze international energy and environmental issues such as climate change, using a detailed, technology rich modeling framework. We then present three different types of application. First, the model is applied to conduct the cost-effectiveness analysis of Greenhouse Gas (GHG) emission abatement, whereby constraints on CO_2 emissions are added to the base case formulation. The model then computes the cost-efficient response of the energy system to these emission targets. Second, we address the issue of "who pays"' for emission reductions (whereas the cost-effictiveness analysis addressed the "who acts" issue). More precisely, we use the model to devise and evaluate certain allocation rules for attributing initial emission rights to regions in a cap-and-trade system. Third, we use World MARKAL in a cost-benefit mode, i.e. we augment the model with damage costs resulting from climate change, and run the integrated model without any pre-set tar-

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[1] The applications reported here were made with a MARKAL model. The TIMES incarnation was developed more recently and will progressively replace MARKAL in future applications. The two models share many features, including those deiscussed here. In addition, TIMES incorporates new features that are briefly discussed in the Appendix.

gets on emissions or concentration. We then analyse cooperative and non-cooperative decisions by regions when confronted to the threat of damages. This last application makes systematic use of game theoretic concepts.

1. Introduction

In this article, we present the new multiregional global MARKAL-TIMES[2] model and several recent applications to global energy-environment issues. The development of the model was motivated by the need to analyze international energy and environmental issues such as climate change. Two early versions of the World model were developed through collaborations with the Energy Information Administration (EIA) of US Department of Energy (USDOE)[3] and of the International Energy Agency (IEA). The model discussed in this paper differs from these two initial versions by a number of technological additions and overall calibration. The model has evolved from the original MARKAL model (Fishbone and Abilock, 1981; Kanudia and Loulou, 1998, 1999; Loulou and Lavigne, 1996) and thus incorporates the many enhancements that have occurred since, plus new ones. The model reported here is a 15 region global, energy technology model that computes an inter-temporal equilibrium over a 55 year horizon.[4] A detailed, exhaustive description of MARKAL appears in (ref: MARKAL doc). We present below the key model features:

Economic rationale. The model computes a multi-regional, dynamic partial equilibrium on energy and emission markets over eleven 5-year periods centered on years 2000, 2005,..., 2050. The equilibrium is based on the maximization of discounted total (suppliers' plus consumers') surplus[5] using Linear Programming. It covers all energy forms from extracted and imported primary energy to secondary energy, final energy, and energy services (end-use useful energy). Each sector and subsector is represented as a set of technologies that consume and

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[2] The applications reported here were made with a MARKAL model. The TIMES incarnation was developed more recently and will progressively replace MARKAL in future applications. The two models share many features, including those deiscussed here. In addition, TIMES incorporates new features that are briefly discussed in the Appendix.

[3] For more information on the SAGE model variant developed at EIA, see the documentation residing at: http://www.eia.doe.gov/bookshelf/docs.html.

[4] A TIMES version with a 100-year horizon is in preparation

[5] In the software implementation, the MARKAL-TIMES Linear Program equivalently minimizes the negative of the surplus, i.e. an objective function equal to Discounted Total Cost, that includes:

produce a broad array of energy carriers and materials, and emit substances into the atmosphere. The sets of technologies, energy carriers, materials, and demands, constitute the Reference Energy System (RES) of a region. The model is driven by a set of constant elasticity[6] *demand functions* for all energy services. In the base case, the energy service demands are exogenously specified by scenario for each period and region. Alternate scenarios may be constructed in many different ways, for instance by imposing new constraints and/or taxes on technologies, on emissions, etc., and the model endogenously adjusts the equilibrium in response to the changing prices of energy services. As a result of the equilibrium computation, MARKAL-TIMES produces a *primal solution* consisting of energy flows, as well as investments and operating levels for all technologies, and a *dual solution* consisting of the prices of all energy carriers, emissions, materials, and energy service demands.

Regions. The model is disaggregated into 15 regions (Table 5.1): Africa (AFR), Australia–New-Zealand (AUS), Canada (CAN), China (CHI), Central and South America (CSA), Eastern Europe (EEU), Former Soviet Union (FSU), India (IND), Japan (JPN), Middle-East (MEA), Mexico (MEX), Other Developing Asia (ODA), South Korea (SKO), United States (USA) and Western Europe (WEU). For reporting purpose, they may also be aggregated into four main regions (see Table 5.1). Each regional model is a complete, self-contained MARKAL model. In addition, the 15 models are hard-linked by several energy and emission permit trading variables. MARKAL also distinguishes between the trading of oil and petroleum products produced by OPEC and non-OPEC regions.

Time horizon. The model is run over a 55-year horizon (1998–2052), divided into 11 five-year periods, centered in 2000, 2005, ..., 2050.

Figure 5.1 illustrates the reference energy system of a region in the World-MARKAL model. The number of technologies in brackets illustrates the level of detail of this global model.

Demands. For each region, 42 demand segments cover five end-use sectors: residential (11 segments), commercial (8 segments), agriculture (1 segment), industry (6 segments) and transportation (16 segments). Each demand segment is serviced by end-use technologies, whose number varies depending on the segment (see numbers in brackets in each box of

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[6] Other forms of demand functions are possible

Table 5.1. List of regions in World-MARKAL

Code	Region	Aggregated Region (4)
AFR	Africa	DC (Developing Countries)
AUS	Australia-New Zealand	OECD
CAN	Canada	OECD
CSA	Central and South America	DC
CHI	China	ASIA
EEU	Eastern Europe	FSU+EE
FSU	Former Soviet Union	FSU+EE
IND	India	ASIA
JPN	Japan	OECD
MEX	Mexico	DC
MEA	Middle-East	DC
ODA	Other Developing Asia	ASIA
SKO	South Korea	ASIA
USA	United States	OECD
WEU	Western Europ	OECD

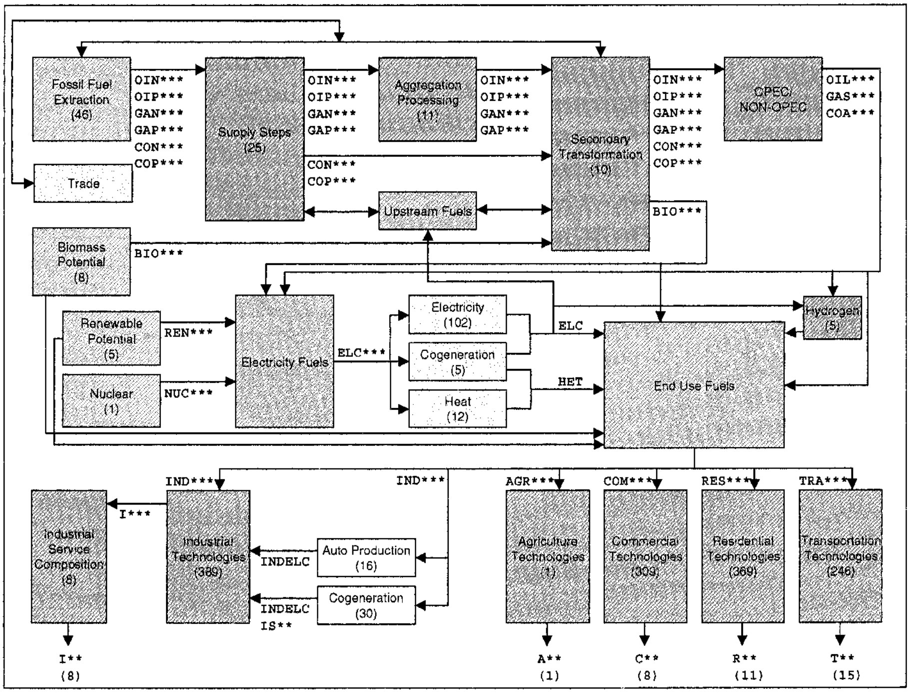

Figure 5.1. The reference energy system of a region in World-MARKAL

Figure 5.1). They are projected up to 2050 using socio-economic drivers, such as population and GDP, and elasticities of the service demands to these drivers.

Supply. The energy production sector is represented by three distinct blocks: primary production, secondary transformation, and production of electricity and heat. Primary production delivers the raw fossil fuels, biomass, and nuclear fuel. Crude Oil, gas and coal resources are provided for each region. They cover located reserves, reserve growth and new discovery for conventional oil, mined oil sands, ultra heavy oil, shale oil, natural gas, hard coal, and brown coal. Unconventional and unconnected gas resources are also available. Costs of reserves and extraction technologies reflect the actual increase of extraction cost with the cumulative level of extraction. Primary biomass covers solid biomass, landfill gas, liquids from biomass, energy crops, industrial and municipal wastes. This block also contains the potentials for other renewable energy forms (geothermal, hydroelectricity, wind, etc.). Secondary transformation transforms the primary energy forms into fuels for end-use sectors. The technology representation in these two blocks is generic. The primary production of each primary energy carrier is configured as a 3-step supply curve, and the secondary transformation section mainly relies on a flexible refinery technology.

The production of electricity and heat is technologically explicit and detailed. Available power plants include technologies such as conventional pulverized coal, integrated coal-gasification combined cycle (IGCC), combined cycle gas turbine (CCGT), diesel plants, fuel cells, biomass plants, nuclear, hydro-electricity, wind, solar, etc. Co-firing power plants are available for both coal and gas fired plants. Electricity production (and consumption) is tracked in three seasons and two divisions of the day, resulting in six time slices annually. In addition, there is a power constraint representing peak electricity requirements. Heat is tracked by season only (3 time slices). Fuels produced and consumed in each sector generally represent a mix of different energy commodities (e.g. a mix of distillates, gasoline and other oil products for the residential sector).

Hydrogen may be generated by electrolysis of water, reforming of natural gas and partial oxidation of coal, with and without CO_2 capture. It can be consumed either as a pure commodity in transportation sector or as a mix with natural gas in industry and residential/commercial sectors.

Emissions. The model tracks emissions of CO_2, CH4, and N2O from the energy system. Combustion emissions are based on the fuel inputs of technologies. For fugitive emissions (due to losses and venting) and emissions related to non-energy consumption (like feedstock), emission coefficients are specified at the technology level.

Interregional trade. The interregional trade of natural gas, liquefied gas, and coal is endogenously modeled. Thus, the amount and price of each of these traded commodities is endogenously computed as part of the equilibrium solution. Electricity is not traded at the interregional level, except between USA and CAN, where exchanges are fixed, by default, at their 2000 values. In contrast, the prices of traded crude oil and refined petroleum products are exogenously specified to reflect the non-competitive world market for oil. Each region is free to import any amount of crude oil and/or refined petroleum product at a fixed exogenous price. Exports are then adjusted ex-post to balance imports at the world level. International trade of hydrogen is not included.

Zero-emission-technologies and carbon sinks. Because of its impact on the cost of mitigation carbon, sequestration of carbon is modeled. It includes: capture, which may occur at power plants (IGCC, pulverized coal, NGCC, solid oxide fuel cell SOFC) and at hydrogen plants; storage (oil/gas fields, coalbed methane recovery, aquifers, deep ocean, mineralization) and transportation between capture and storage. Sequestration by forests is also available. Capture at industry level is not included in this version of the model.

Economic parameters. GDP and all costs and prices are expressed in constant (year 2000) US dollars, calculated at market exchange rates (MER) for other regions. Investment, variable and fixed costs of technologies vary across regions in order to reflect differences of labor costs and productivity, land costs, project boundaries. The overall annual discount rate used for calculating the net present value of the system is fixed at 5%. Some sector and region specific discount rates (hurdle rates) are also used for annualizing investment costs, to reflect the financial and behavioral characteristics appropriate to each economic agent.

In the rest of this article, we present three different types of application of the World MARKAL model. Section 2 is devoted to an application of the model to the cost-effectiveness analysis of Greenhouse Gas (GHG) emission abatement, whereby constraints on CO_2 emissions are added to the base case formulation. The model then computes the cost-efficient response of the energy system to these emission targets. Section 3 addresses the issue of 'who pays' for emission reductions (whereas the cost-effeicient analysis of Section 2 addressed the 'who acts' issue). More precisely, we use the model to devise and evaluate certain allocation rules for attributing initial emission rights to regions in a cap-and-trade system. In Section 4, we use World MARKAL in a cost-benefit mode, i.e. we augment the model with damage costs resulting from climate change, and run the integrated model without any pre-set targets on emissions or concentration. We then analyse cooperative and non-cooperative decisions by regions when confronted to the threat of damages. Section 4 makes systematic use of game theoretic concepts.

2. Cost-effectiveness analysis of CO_2 emission abatement

The objective of this application is to present a cost-effectiveness analysis of global and regional greenhouse gas emission reduction scenarios (Labriet et al., 2004). After presenting the base case main technological and economic assumptions (Section 2.1), and results (2.2), we turn to the energy, technology, and emission results for a globally constrained-CO_2 scenario (2.3 and 2.4) and end this section with a discussion of the results (2.5).

2.1 The base scenario (BAU-A1B)

The initial period (period 2000, i.e., 1998–2002) is calibrated to the International Energy Agency statistics and balances of year 1999 (IEA, 2001). For the subsequent periods, the base scenario is calibrated to the A1B reference scenario modeled by the Asian Pacific Integrated Model (AIM) for the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic and Swart, 2000). This scenario is one of the most frequently cited in the literature and used in the post-SRES mitigation scenarios (Morita and Robinson, 2001). The A1B scenario is roughly characterized by the objective of maximization of income by people and further globalization, rather than pursuing environmental goals and regionalization (Bollen et al., 2000).

Projecting long-term energy and emission scenarios involves many assumptions that are detailed in Labriet et al. (2004). First, calibration is undertaken by changing the final demands for energy services. Future service demands are projected using general demographic and economic drivers, such as population and GDP projections from the A1B scenario (European Commission, 2003; Nakicenovic and Swart, 2000). End-use demands are then derived from these drivers via elasticities. Calibration is carried by imposing exogenous constraints, to reflect non-economic decisions or to reproduce certain behavioral characteristics of observed markets. The rate of penetration of several new technologies and the rate of change of the fuel proportions at end-use level are exogenously constrained. For example, the minimum level of total renewable electricity generation is exogenously controlled in order to reflect the high levels of renewable energy proposed in the A1B scenario. Moreover, the installed capacity of nuclear power plants is exogenously fixed at the level provided in the A1B scenario (which is high), reflecting the fact that the decision to invest or not in nuclear plants in mainly motivated by non-economic factors. All the constraints are progressively relaxed in future periods.

2.2 Energy/emission trajectories in the base case

The analysis of energy/emission trajectories aims at exploring the technology decisions computed by the model. Although available for the 15 regions of the model, results are presented for the four aggregated regions only (OECD, FSU+EE, ASIA, and DC). The main results of the calibration process are illustrated in Figure 5.2: Primary and final energy consumption computed by World-MARKAL. The final energy results are very close to A1B scenario modeled by AIM (differences are less than 5%). The analysis of the final energy and emissions per sector shows the following trends:

- The main contributors to emissions depend on the existing structural characteristics of regions. In 2000, they are respectively (Table 2): transport and electricity in OECD, industry and electricity in FSU+EE and ASIA, industry, transportation and electricity in equal share in DC. Two important changes occur in later periods: the contribution of emissions by the electricity sector decreases in all regions, except FSU+EE where it stabilizes, and the contribution by the transportation sector remains at the 2000 value or decreases slightly. The reasons are respectively the increase of renewable and nuclear in electricity generation and the penetration of biomass, natural gas and hydrogen[7] in the transportation sector.
- In industry, we observe the substitution of oil and coal by electricity and natural gas while electricity increases its share of final energy consumption in commercial and residential (see Table 5.5).

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[7] Emissions related to the production of hydrogen are allocated to the upstream sector, so that end-use consumption of hydrogen is emission-free. The increase of emissions associated with the production of hydrogen compensates for the decrease of refinery emissions due to the decrease in the needs for oil products.

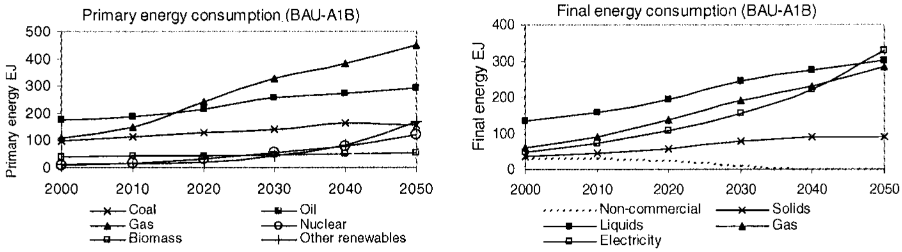

Figure 5.2. Primary and final energy consumption in the base scenario

Energy shares in transportation are the direct result of exogenous constraints forcing the penetration of alternative fuels (biomass, electricity, natural gas and hydrogen). Because no major structural change is expected in the agriculture sector, no competition is allowed in this sector, so that energy shares remain almost constant and reflect assumptions. Changes in end-use sectors reflect the structural transition toward higher shares of advanced and non-fossil energy.

The price of gas increases slightly in all regions, from 0.3% to 1.5% per year, depending on the availability and cost of local resources and on the prices and nature of imports (Note that the annual increase of marginal cost of gas in the A1B scenario is around 1.4% for gas, see Nakicenovic and Riahi, 2002). The price of coal varies by −1% to +0.4% per year between 2000 – 2050, reflecting that coal is an abundant resource. Since the price of oil is exogenous, its increase reflects the assumption of an annual growth of 0.2 to 0.9% (Note that the annual increase of oil price in the A1B scenario is less than 0.8% between 2000 – 2050, see Nakicenovic and Riahi, 2002).

We now present some technological detail in the two sectors that contribute most to emissions, i.e. electricity generation and transportation. The following trends are observed:

- In the electricity sector, new coal capacity is in the frorm of pulverized coal plants, the least expensive option considering both capital and operating costs. Although more efficient, new IGCC plants do not penetrate. Combined Cycle Gas Turbines (CCGT), characterized by a low investment cost and high efficiency, are the preferred technology for new gas capacity, replacing the phased-out capacity and producing the new electricity needed. The gas fuel cell also penetrates to satisfy the need for decentralized electricity capacity. The need for decentralized electricity also motivates the

Table 5.2. Emission contribution of activity sectors in the base scenario

	OECD		FSU+EE		ASIA		DC	
BAU-A1B	2000	2050	2000	2050	2000	2050	2000	2050
Agriculture	1.2%	1.5%	2.0%	2.4%	2.1%	1.1%	1.9%	1.7%
Com/res	12.6%	17.1%	15.6%	13.7%	8.6%	13.7%	9.7%	10.9%
Industry	18.2%	20.1%	31.2%	29.2%	28.8%	29.4%	26.6%	41.2%
Transport	30.4%	27.5%	9.6%	6.1%	16.0%	16.5%	27.8%	21.6%
Electricity	30.5%	21.8%	32.5%	34.6%	37.1%	33.8%	27.1%	20.0%
Upstream	7.0%	12.0%	9.1%	14.0%	7.3%	5.5%	6.8%	4.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

penetration of some new capacity of decentralized oil fired plants. New capacity of nuclear and renewable (geothermal, hydroelectricity, wind and solar) is driven by the exogenous lower bounds. All the available hydro capacity and shallow geothermal penetrate (up to their upper bounds), being the cheapest renewable electricity sources.

- Transportation technologies: their penetrations are in part determined by some exogenous constraints, such as lower bounds on alcohol fuels, gas and electricity required to simulate the base case. In developing countries, upper bounds on alcohol fuels were also applied to avoid the too rapid penetration of alternative vehicles. The results indicate that electric cars, light trucks and buses, natural gas cars, light / medium / heavy / commercial trucks and buses and finally hydrogen cars and light trucks penetrate the market.

2.3 Carbon constrained scenario (550-A1B)

The constrained scenario assumes the stabilization of atmospheric CO_2 concentration at 550 ppmv. The emission path generated by the AIM model to achieve this target is applied as a series of global constraints on annual emissions in each period. This choice reflects the frequent reference to this target in modeling and political discussions (Morita and Robinson, 2001). The target is applied at the world level, to ensure cost efficiency of the response. Hence, the mitigation scenario is equivalent to a situation where all regions of the world participate in a free CO_2 permit market. Note also that the initial allocation of emission rights is not specified in this run, since it has no impact on overall efficiency (see Sections 3 and 4 for analyses of emission rights). The analysis compares energy and technology options in the constrained scenario (550-A1B) and in the base scenario (BAU-A1B). The study focuses on

Table 5.3. Price of CO_2 reduction

$(US\$_{2000}/tCO_2)$	2000	2010	2020	2030	2040	2050
550-A1B	0	32.4	60.4	62.6	54.1	92.8

CO_2 mitigation, as the carbon constraint represents the stabilization of CO_2 concentration. The generation of electricity by coal plants is not upper bounded in the mitigation scenario, contrary to the base scenario. The expectation is that any new investment in new coal plants would be motivated by the possibility to capture and sequestrate carbon, and that these new coal technologies would also control the local pollutants emitted. This expectation is borne out in the results.

2.4 Results for the 550-A1B scenario

The marginal price of CO_2 in the constrained scenario reaches 92.8 $US\$_{2000}/tCO_2$ in 2050 (Table 5.3). The temporary decrease of the price in 2040 is explained by the availability of more advanced wind technologies. The 2010 price (\$32) appears to be in the high range of carbon prices estimated by other studies in the context of the Kyoto Protocol with a global trading of carbon permits (4 – 44 $US\$_{2000}/tCO_2$) (Weyant, 2000). This is because the MARKAL emission constraints are more severe than those required by the Kyoto Protocol. The annualized incremental cost, expressed as a percentage of GDP in 2000, represents 0.8% of GDP.[8]

The reduction of emissions depends on mitigation options available in each region. Technological options for reducing CO_2 include (Moomaw and Moreira, 2001; Riahi and Roehrl, 2000): more efficient conversion and combustion of fossil fuels (enhanced energy conservation); switching away from carbon-intensive fuels such as coal; suppressing leakages; de-carbonization of flue gases and fuels, and CO_2 storage. Another mitigation 'option' is the price-induced reduction of energy service demands. The options, which are identified by MARKAL as cost-effective to meet the 550 ppmv target, are:

Sequestration: Capture of CO_2 at upstream level (leakages), at power plants and at hydrogen plants, and sequestration in deep aquifers. Sequestration by forests is also selected. Sequestration accounts

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[8] The abatement costs are evaluated per unit of GDP (cost/GDP) to facilitate comparisons; they do not represent a variation of the GDP itself.

for 40 to 63% of total CO_2 reduction in 2050 (Table 5.4). Some additional remarks:

- The cumulative amount of CO_2 sequestered remains far below the total potential for sequestration. Sequestration by forests and deep saline aquifer are the preferred options, because of their low costs.
- One of the impacts of the availability of CO_2 sequestration options is the joint role of coal and gas in electricity generation (Figure 3). CCGT (gas) dominates in the initial periods, when carbon price is moderate. However, it is phased out under higher carbon prices in later periods, when the efficient and cheap coal SOFC with CO_2 capture becomes available. Electricity generation by gas fuel cells remains in base and mitigation scenarios to satisfy needs for decentralized electricity. Other studies confirm the robustness of CCGT as it bridges the transition to more advanced fossil and zero-carbon technologies (Nakicenovic and Riahi, 2002).

Biomass in electricity: The role of renewables other than biomass in electricity generation does not increase, because of already large penetration of renewable in the base scenario. Electricity from biomass plants and co-combustion of coal and biomass in coal power plants increase.

Biomass in transport: The substitution of oil by alcohols derived from biomass in the transportation sector increases, while the other alternative fuels (electricity, natural gas and hydrogen) remain unchanged compared to the base scenario (Table 5.5). Investments in more efficient oil vehicles are also observed. Availability of biomass results in regional variations; for example, biomass represents more than 30% of transportation energy in AFR and CSA, these regions being biomass rich. High cost of hydrogen consuming and producing technologies inhibits their further penetration. However, the production of hydrogen uses CO_2 capture in the 550 scenario. This result is in agreement with other studies observing that biomass is an important fuel for transportation as a replacement of oil, while hydrogen starts playing an increasing role after the mid-century, when solar and nuclear hydrogen (truly zero-carbon options) become competitive and replace hydrogen produced from natural gas (Riahi and Roehrl, 2000).

Cleaner fuels in other end-uses: In the other end-uses, the substitution of oil and coal by natural gas and electricity in industry, observed in the base scenario, is strengthened, while no sig-

Table 5.4. Regional CO$_2$ reduction and sequestration

	Reduction re. BAU		Sequestration re. total reduction	
	2005	2050	2005	2050
OECD	−9.3%	−38.7%	−24.1%	−63.4%
FSU+EE	−11.2%	−42.9%	−50.7%	−56.6%
ASIA	−9.6%	−40.3%	−19.3%	−39.5%
DC	−14.5%	−36.9%	−37.4%	−47.3%
WORLD	−10.5%	−39.0%	−29.8%	−48.8%

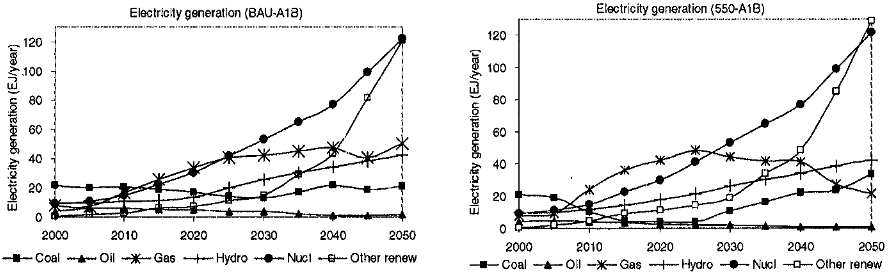

Figure 5.3. Electricity generation by fuel in the base and the reduction scenarios

nificant changes of the final fuel shares are observed in residential/commercial sectors (Table 5.5).

Demand reduction: The price-induced reduction of elastic demands is small and contributes accordingly little to emission reductions. It is less than 3% in commercial and residential sectors, except for demands depending on electricity only (residential lighting, residential electric appliances, commercial refrigeration, commercial electric office equipment and commercial other), which are reduced between 6 and 19%. The reduction in demands is between 1 and 7% in industry, less than 2.1% for road transportation, and reaches 14% for aviation.

Energy price variations depend on regions, but the general trend is an increase of 50% to 150% in electricity prices compared to base scenario and an increase of up to 10% in natural gas prices. No clear trend is observed for coal prices. The increase in electricity price provokes a decrease of 4.5% in electricity consumption at world level in 2050; the reduction of electricity consumption is higher in the first few periods (reaching 8.7% in 2010), when electricity is more expensive.

Table 5.5. Shares of final energy in end-uses in the base and the constrained scenarios

		BAU-A1B		550-A1B
		2000	2050	2050
Industry	Biomass	5.0%	4.0%	4.4%
	Coal	20.4%	8.5%	7.5%
	Gas	28.9%	37.4%	39.2%
	Heat	0.5%	0.6%	1.5%
	Oil	27.1%	18.7%	14.6%
	Elc	17.4%	29.8%	31.8%
	Other	0.7%	0.9%	0.9%
	Total	**100%**	**100%**	**100%**
Comm/Resi	Biomass	33.3%	4.2%	4.6%
	Coal	5.1%	9.8%	9.3%
	Gas	24.6%	19.4%	20.2%
	Heat	5.7%	2.3%	2.4%
	Oil	17.6%	23.6%	23.9%
	Elc	13.3%	39.7%	37.9%
	Other	0.2%	1.0%	1.6%
	Total	**100%**	**100%**	**100%**
Transport	Biomass	0.4%	11.1%	22.6%
	Coal	0.0%	0.0%	0.0%
	Gas	1.0%	12.2%	12.3%
	Hydrogen	0.0%	12.2%	12.3%
	Oil	97.7%	58.7%	47.4%
	Elc	0.9%	5.7%	5.5%
	Total	**100%**	**100%**	**100%**

2.5 Discussion

Sensitivity analyses were undertaken to understand the role of the constraints on coal and renewable electricity generation (see Labriet et al., 2004). These analyses confirm that the assumed level of non-emitting electricity generation is a crucial assumption for projecting future emissions and analyzing future CO_2 policies (even more so than the assumed limit on the consumption of coal by power plants). This conclusion clearly justifies the definition of an alternative base scenario with reduced nuclear and renewable electricity generation. The results of this alternate base scenario are presented in Labriet et al. (2004).

Moreover, the analysis of CO_2 abatement options available under a global carbon constraint were completed by sensitivity analyses on the availability of CO_2 sequestration options and end-use demand elasticities (see Labriet et al., 2004). Given the uncertainties related to CO_2

capture and sequestration, and the important role played by sequestration in mitigating emissions, we have explored "second best" strategies where sequestration was forbidden. Without sequestration, penetration of biomass and gas increases, and end-use demands reduce further; and the overall cost of reduction doubles. In another sensitivity scenario, demands are assumed inelastic. The main effect is an increase in the electricity consumption and in the sequestration of CO_2.

The analysis of the base and carbon constrained scenarios confirms and refines several conclusions observed by other models: (a) the level of non-emitting electricity generation in the base scenario is a crucial assumption for defining CO_2 reduction opportunities; (b) CO_2 capture and sequestration competes directly with renewable electricity generation and contributes to a major reduction in the marginal cost of CO_2; (c) the primary consumption of coal may increase in the long term when associated with the capture of flue gas CO_2 at power plants; (d) in transportation, the substitution of oil by biomass is robust and much preferred to the other alternative technologies prior to 2050; e) the price-induced reduction of elastic demands also contributes to the emissions reduction, although in modest proportion; it captures a great deal of the interaction between the energy system and the economy that was not previously accounted for in earlier bottom-up energy models. The resulting annualized cost of CO_2 abatement remains under 1% of the GDP in 2050 for the stabilization of CO_2 concentration at 550 ppmv in the A1B scenario. The deeper analysis of hydrogen production and end-uses technologies, the availability and costs of CO_2 capture and sequestration, as well as the explicit modeling and calibration of non-CO_2 greenhouse gases would deserve more attention.

3. Application to GHG permit allocations

This application examines a permit trading system where all countries participate to achieve a long-term GHG stabilization target (Vaillancourt, 2003; Vaillancourt *et al*, 2004). The main objective is to propose CO_2 permit allocation schemes that lead to a fair distribution of net abatement costs among world regions, in an assumed cap-and-trade regime. The World-MARKAL model is used to calculate the regional abatement costs, which then become the basis for the proposed allocation. For this purpose, two runs of the model are required. First, the base scenario is calibrated to the A1B reference scenario of IPCC (Nakicenovic and Swart, 2000). Then, a global emission trajectory from the AIM model is used as a global constraint. This trajectory is compatible with the stabilization of CO_2 concentration at 550 ppmv (Morita and

Robinson, 2001). We present here the methodology and the results of two allocation schemes. Note that the version of the model used for this application is an earlier one that differs somewhat from the version used for the cost-effectiveness application of Section 2. Consequently, the results cannot be compared across the two studies.

3.1 Equity issues

Many equity principles and criteria have been proposed to allocate emission rights/permits (egalitarianism, polluter pays, historical responsibility, ability to pay, grandfathering, etc.) or abatement costs (horizontality, verticality, comparable costs, etc.) (Banuri et al., 1996; Bayer, 1999; Blanchard *et al*, 1998, 2000; Rayner et al., 1999; Rose et Stevens, 1993; Rose et al., 1998; Torvanger and Godal, 1999). Authors also propose several allocation proposals during the pre-Kyoto period. Today, more and more authors are interested in long-term stabilization scenarios involving the participation of all countries (Berk and Den Elzen, 2001; Den Elzen et al., 1999; Gupta and Bhandari, 1999; Onigkeit and Alcamo, 2000; Shukla, 1999).

Among others, a decision aid tool has been proposed to provide relevant information on various equitable permit allocation schemes to the decision makers and negotiators (Vaillancourt, 2003; Vaillancourt and Waaub, 2003; 2004). A dynamic multicriterion model is used to share a global amount of permits between 15 world regions using 11 allocation criteria, which represent different visions of equity. It provides relevant information to decision-makers. However, the subsequent economic analysis, using the World-MARKAL model, revealed unacceptable cost distributions in some cases. For instance, some regions become wealthier in the stabilization context than they would otherwise do in the Base Case. The cause of such anomalies was tracked to the inability of the traditional criteria to fully reflect the regional differences in the *need to emit* and the *opportunities to abate*, two criteria that should also be considered for permit allocations. However, these criteria are difficult to take into account at the same level as the other criteria, since it is not easy to translate them into straightforward indicators. They depend upon a complex interaction of multiple factors. We now elaborate on these affirmations.

The *need to emit* depends upon diverse factors that evolve over time, including climate, geography, structure of the economy, level of economic development, demographic profile and domestic energy resources at any time present and future. The traditional criteria, such as population and GDP, do not adequately reflect these factors, especially in the context of widely different economies. For instance, population per se is not an adequate measure of the need to emit. Only the emissions resulting from a population's actual needs at each period of its development are relevant. Let us examine the example of Canada and Morocco, two countries with similar populations. We observe two large differences in their needs to emit: space conditioning and average transportation distances. Looking at the options available: space heating can use oil, gas, electricity, or wood. Electricity is the only option for space cooling. Finally, not all people in Morocco have access to energy intensive amenities now, but will surely do so at some point in the future. Similarly, GDP may not accurately reflect emission needs. Consider country A, with a GDP mainly composed of a service sector, and country B, with similar GDP value, where conventional industry has a significant share. If permits were allocated based on GDP, A and B would get equal amounts, and A would make money by selling some of them to B. Is that fair? Country A developed its service sector in pursuit of its own welfare, not to reduce GHG emissions. In summary, there is a very complex network of forces evolving over time, which determines the business-as-usual (BAU) emission of countries.

The *opportunity to abate* is based on resource endowment and the inertia of the infrastructure; different countries have different abatement potentials. For example, a region may have untapped hydroelectricity potential, while another may have already developed its own potential. A region may have poor industrial equipment and practices, leaving room for efficiency gains, while another may be much more efficient already, leaving less room for further improvement. A region may have a large coal based electricity system, with very low growth, while another may have an electricity system also dominated by coal, but growing rapidly. Since the latter region has the option to make alternate investments, its reductions over the BAU emissions will be cheaper. As in the case of the need to emit, there are numerous interacting factors at play here, which are hard to analyze in isolation from one another.

We describe an approach to address these two criteria more explicitly. We propose to use the net regional abatement costs (calculated by the global bottom-up energy model World-MARKAL) as an indicator capturing these two criteria. Allocation schemes based exclusively on a fair distribution of net costs are therefore proposed as a complement to allocation schemes based on other allocation criteria.

3.2 Methodology to allocate permits

Two permit allocation schemes are proposed in this paper. At each period, the objective is to equalize either the net abatement costs per unit of GDP-ppp (purchase power parity) or and the net abatement cost per unit of GDP-ppp Squared. The first scheme (S-GDP) respects a new form of the horizontality principle, since it equalizes the net costs across regions as a percent of GDP. The second scheme (S-GDP2) reflects a form of the verticality principle, since it aims at allowing more permits to the poorest regions, those for which the GDP is the lowest.

The model first run without constraint on emissions, to obtain the system's reference cost, and then run with a global constraint on emissions to obtain the optimal (efficient) emission level $E_i(t)$ and the new system cost. The *gross* abatement cost $C_j(t)$ of each region is the difference between the two system costs for that region. The *net* abatement cost $x_i(t)$ is defined as the gross abatement cost $C_j(t)$ plus the cost of buying permits (which depends on the allocation of emission rights, and may be positive or negative), i.e.:

$$x_i(t) = C_i(t) + y_i(t) \cdot P_W(t) \tag{5.1}$$

Where $y_i(t)$ is the (as yet unknown) quantity of permits purchased by region i, and $P_W(t)$ is the price of permits (also computed by the model). Note that the global net abatement cost is equal to the global gross abatement cost $C_W(t)$ provided by the model. In order to equalize net abatement costs per GDP across regions, the following equations must be satisfied:

$$\begin{aligned}\frac{x_i(t)}{\mathrm{GDP}_i(t)} &= \frac{x_j(t)}{\mathrm{GDP}_j(t)} = \frac{x_k(t)}{\mathrm{GDP}_k(t)} \\ &= \frac{\sum_i x_i(t)}{\sum_i \mathrm{GDP}_i(t)} = \frac{C_w(t)}{\mathrm{GDP}_w(t)} = K,\end{aligned} \tag{5.2}$$

i.e.,

$$x_i(t) = K \cdot \mathrm{GDP}_i(t) \tag{5.3}$$

or, using (5.1) above

$$y_i(t) = \frac{1}{P_W(t)}[K \cdot \mathrm{GDP}_i(t) - C_i(t)]. \tag{5.4}$$

Finally, the allocation of rights $a_i(t)$ to region i is equal to emissions plus permits sold:

$$a_i(t) = E_i(t) - y_i(t). \tag{5.5}$$

For the second allocation scheme S-GDP2, simply replace GDP(t) by GDP$(t)^2$ throughout. These allocation schemes lead to situations where there are buyers and sellers of permits.

3.3 Results

First, this section presents the efficient solution of the World-MARKAL model, i.e., emission reductions and gross abatement costs of regions (3.3.1). These results are obtained by comparing the results of the constrained scenario to those of the base scenario (excluding permit trading). The solution is globally optimal, irrespective of the allocation of permits. The second part (3.3.2) consists in calculating and analyzing the net abatement costs of regions (including permit trading), for both allocation schemes.

3.3.1 Emission reductions and gross costs. Global cooperation leads to the equalization of the marginal abatement costs across all regions. The world marginal costs ($/t), as well as the global percentages of reduction (%), are presented for each period in Table 5.6. The decrease in the marginal cost in 2020 is related to an increase of emissions in the AIM's stabilization trajectory, and consequently, a very small reduction between 2010 and 2020. The increase in the marginal cost for the following periods is explained by higher percentages of reduction and by the continued increase in economic activity in all regions.

The emission reductions in each region are presented in million tonnes of carbon (MtC) in Table 5.7 for each period. This table also shows the cumulative percentages (%) of reduction, which represent the total quantities of emission reductions over the entire horizon. The last two columns show the gross abatement costs in billion dollars (G$) and per unit of GDP-ppp (%GDP). Since the marginal cost is uniform, the regions where the reductions are most important are generally those for which the gross cost is the highest. For the world, the emission reductions grow from 1950 MtC in 2010 (21%) to 6190 MtC in 2050 (45%), for a total discounted cost of 8043 G$.

Table 5.6. World marginal abatement cost

Period	2000	2010	2020	2030	2040	2050
Marginal cost ($/t)	0	50	35	158	177	423
Global reduction (%)[a]	0	21	24	38	40	45

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[a] The global reduction (%) is the relative difference between the emission of the base scenario (A1B) and that of the constrained scenario (stabilization at 550 ppmv).

Table 5.7. Emission reductions and gross abatement costs

	Emission reduction (MtC)							Gross cost	
Period	2000	2010	2020	2030	2040	2050	%cum	G$	%GDP[a]
Africa	0	191	349	596	660	649	45	767	0.73
Asia	0	92	158	409	427	385	29	520	0.34
Australia-NZ	0	16	38	78	104	133	35	70	0.40
Canada	0	21	31	71	64	56	25	111	0.42
China	0	160	364	950	1243	1185	32	1518	0.58
Eastern Europe	0	43	35	64	77	86	25	103	0.26
FSU	0	116	121	245	276	434	22	464	0.61
India	0	140	224	488	493	346	39	521	0.41
Japan	0	20	26	56	47	53	14	72	0.07
Latin America	0	131	187	278	475	932	38	919	0.55
Mexico	0	48	107	214	286	345	40	395	0.69
Middle-East	0	89	107	340	392	709	24	746	0.80
South Korea	0	26	29	49	52	50	22	68	0.15
United States	0	720	812	910	647	518	36	1316	0.39
Western Europe	0	139	202	262	306	308	21	452	0.15
World	0	1950	2790	5010	5550	6190	31	8043	0.42

[a] This means that the abatement costs are evaluated per unit of GDP (cost/GDP), i.e., according to the size of the economy of the region, to facilitate the comparisons. However, they do not represent a variation of the GDP itself (reduction or increase in the size of the economy).

These results illustrate quite well the need for cooperation in reducing global emissions. Some regions reduce more than others, because they have more abatement opportunities, and consequently, incur a higher gross abatement cost. A good permit allocation scheme is meant to correct inequities arising from these widely different gross costs. The distribution of gross costs, in space and time, is influenced by the economic growth rate of regions. When the projected growth is strong, a part of the reduction is carried out naturally by energy efficiency improvements with the penetration of new technologies that are necessary to satisfy the energy demand increase. Consequently, in terms of percentages of reduction compared to their base emissions, some regions must reduce more. The developing countries should generally reduce their emissions more than other regions, like Africa (45%), the Latin America (38%), India (39%) and Mexico (40%).

3.3.2 Permit trading and burden sharing: equalizing net abatement costs. It is now possible to calculate the net abatement costs for the two permit allocation schemes: S-GDP (Table 5.8)

Table 5.8. Permit allocations and net costs for the S-GDP scheme

Region	% Allocation		Gross cost	Trading	Net cost[a]	
	2010	2050	B$	+/−	B$	%GDP
Africa	5.8	7.7	767	−377	391	0.37
Asia	7.2	8.0	520	197	717	0.47
Australia-NZ	1.5	1.6	70	−17	53	0.03
Canada	1.9	1.2	111	−40	72	0.27
China	15.2	18.1	1518	270	1788	0.68
Eastern Europe	1.9	1.8	103	97	200	0.49
FSU	9.6	9.0	464	122	586	0.78
India	4.2	8.3	521	10	530	0.42
Japan	3.6	1.2	72	118	190	0.18
Latin America	5.8	7.9	919	−135	784	0.47
Mexico	2.5	4.2	395	−22	373	0.65
Middle-East	9.5	10.3	746	−307	439	0.47
South Korea	1.9	1.4	68	99	167	0.38
United States	17.3	11.0	1316	−222	1094	0.32
Western Europe	12.2	8.3	452	206	658	0.22
World	100.0	100.0	8043	0	8043	0.42

[a] With this scheme, the net abatement costs per unit of GDP (%GDP) are equalized across regions at each period. However, because of the discounting of the trading costs on one hand and of the GDPs on the other hand, the net abatement costs per unit of GDP percentages are not identical in discounted units.

and S-GDP2 (Table 5.9). Only the portion related to permit trading varies from one allocation scheme to the other (the gross costs do not). The permit allocation results are presented in terms of fractions of total permits (%) allocated to each region in periods 2010 and 2050. The net discounted costs (over the whole horizon) are presented in absolute terms (B$) and as a percentage of GDP. Their comparison with the gross abatement costs is interesting; it is thus possible to see which regions must buy or sell permits (columns identified by +/−), and therefore see an increase or decrease of their net abatement cost.

According to the S-GDP scheme, the fraction of permits allocated to the United States is the most important in 2010 (17.3%). China (15.2%) and Western Europe (12.2%) also obtain a significant fraction of permits. In 2050, the allocation to the United States decreases to 11.0% and that to Western Europe decreases to 8.3%, whereas that of China increases to 18.1%. China and the United States are the regions where the absolute net costs are the highest, respectively 1788 G$ and 1094 G$. China receives less permits than it needs to emit and must buy permits (for 270 G$), whereas the United States receives more permits and can sell

Table 5.9. Permit allocations and net costs for the S-GDP2 scheme

Region	% Allocation		Gross cost	Trading	Net cost	
	2010	2050	B$	+/−	B$	%GDP
Africa	5.8	7.8	767	−429	338	0.32
Asia	7.2	8.0	520	182	702	0.46
Australia-NZ	1.5	1.7	70	−34	37	0.21
Canada	1.9	1.3	111	−64	47	0.18
China	15.2	17.0	1518	532	2050	0.78
Eastern Europe	1.9	2.0	103	53	155	0.39
FSU	9.6	9.3	464	60	523	0.69
India	4.2	8.4	521	−34	487	0.38
Japan	3.5	1.4	72	55	126	0.12
Latin America	5.8	7.5	919	−96	823	0.50
Mexico	2.5	4.5	395	−83	312	0.54
Middle-East	9.4	10.5	746	−367	380	0.41
South Korea	1.8	1.6	68	47	115	0.26
United States	17.5	10.7	1316	−93	1224	0.36
Western Europe	12.2	8.3	452	272	724	0.24
World	100.0	100.0	8043	0	8043	0.42

the surplus (−222 G$). Among the other regions, whose net cost is reduced by the sale of permits, there are Africa, the Latin America and the Middle East, and to a lesser extent, Canada, Australia – New-Zealand and Mexico.

The S-GDP2 scheme aims at supporting more the poorer regions compared to the S-GDP scheme. The permit allocations are very similar to those of the S-GDP scheme in 2010. In 2050, the most significant differences are a decrease in permits allocated to China (17.0%, vs. 18.1% in S-GDP) and to a lesser extent to the United States (10.7% vs. 11%) and to Latin America (7.5% vs. 7.9%). For most other regions, the permits allocated increase. Compared to the S-GDP scheme, the net costs are even higher for China (2050 G$) and the United States (1224 G$). The regions whose GDP is the highest (the United States, Western Europe, China), face an increase of their net costs. The permit sellers are the same in S-GDP and S-GDP2. Only India, which was a buyer of permits for 10 G$ with the S-GDP scheme, becomes a seller of permits for 34 G$ with the S-GDP2 scheme.

3.4 Discussion

Sensitivity analyses were also performed on two aspects of the problem for the S-GDP scheme (see Vaillancourt, 2003 or Vaillancourt et al., 2004 for more details). In the first case, the GDP measure based on the purchase power parity (ppp) is replaced by the market exchange rates (mex). This modification has only a mild impact on the allocations in 2050; the impact on net costs is more perceptible. In general, using GDP-mex benefits more to the developing regions, which receive thus more permits. In the second case, the stabilization level is increased from 550 ppmv to 650 ppmv. This analysis requires the modeling of a new scenario, with a different constraint on global emissions. A higher level of stabilization implies a large decrease in the global abatement cost, from 8043 B$ to 2337 B$. The impact on permit allocations, and consequently on the net costs, is therefore significant.

This economic approach to permit allocations represents one vision of equity among others. While multicriterion approaches aim at combining several (often conflicting) visions of equity to allocate permits, the economic approach proposes a single criterion to obtain allocation schemes, leading to an equitable burden sharing expressed in monetary units. The two approaches are therefore complementary: whereas the first one provides relevant information on various equitable permit allocation schemes (but may lead to negative costs for some regions), the second directly indicates which allocations are needed to obtain an equitable distribution of abatement costs (according to principles such as the horizontality or the verticality).

4. Cost-benefit application: Toward an integrated MARKAL model

The objective of this application was to model cooperative and non-cooperative world climate strategies with an integrated version of the multi-regional MARKAL model, where abatement costs provided by MARKAL are augmented with climate damages. This new approach thus allows cost-benefit analyses that endogenise the level of abatement. We use the integrated model in the framework of cooperative and non-cooperative scenarios, using game-theoretic principles, to evaluate the willingness of regions to cooperate, and the calculation of side-payments to guarantee world cooperation. Note that the version of the model that has been used for this exercise is very similar to the one used for the cost-effectiveness application (Section 2). More detailed description and results are available in Labriet and Loulou (2003, 2004).

4.1 Interdependent strategies

By definition, the conventional cost-efficiency use of MARKAL assumes cooperation of all the regions since the equilibrium computed by MARKAL represents an efficient attainment of an exogenous environmental target, which represents a globally desirable and accepted CO_2 target. This cooperative solution constitutes the first-best solution, and thus the upper or optimistic limit of what is achievable in terms of global cost for the set target. One of the greatest advantages of the cost-efficiency approach is that climate damages, that are very uncertain, need not be explicitly valued. However, a globally optimal (cooperative) solution does not guarantee that every country is better off under this policy, and some countries may free-ride, either to maximize their individual welfare, and then enjoy the pollution abatement brought by the cooperating actors, or to associate with other countries to perhaps collectively gain higher welfare than the grand coalition.

Cost-benefit analysis weighs the costs of reduction against the benefits of reduction (i.e., the cost of damages) to set endogenously the environmental level and the mitigation strategy with the highest net global benefit. It may be the only way to examine abatement policies if targets cannot be set, for instance if countries act in a partially cooperative or non-cooperative manner, as hinted by the limited success of the Kyoto Protocol. The purely non-cooperative framework represents the situation where every region pursues its own best payoffs without coordinating with others, but taking into account the other actors' choices. The so-called *Nash equilibrium* represents the realistic lower end of possible international strategies and it is considered as a threat point: if negotiations toward cooperation break down completely, the Nash situation may well result; in other words, it constitutes a self-enforcing (but inefficient) strategy (Folmer et al., 1998). Intermediate outcomes may also occur, where subsets of regions form separate coalitions that implement internal cooperation, but do not cooperate with other coalitions.

Thus, the coupling of MARKAL and climate damages aims at allowing the integrated assessment of climate cooperative and non-cooperative strategies, where the resulting emissions are endogenously computed.

4.2 Coupling MARKAL and climate damages

Two approaches may be suggested to integrate non-linear and non-convex climate damages costs into a linear programming optimization model like MARKAL. The first approach consists in augmenting the model with the complete set of climatic equations and damage functions. The main drawback of this approach is the inclusion of many constraints in the model, and more particularly some non-linear and non-convex constraints, which in turn make the computation of the equilibrium much more difficult. The second approach is to consider a potential simplification in the representation of climate and damage variables. For the second approach to work, it must first be established that damages are related directly to emissions in some simple manner. In our research, we conjectured that damages might be a function of global cumulative emissions only.

Based on the empirical analysis of climate damages, using 30 contrasted emission trajectories (Nakicenovic and Swart, 2000), a simplified climate model and regional quadratic damage functions of ΔT proposed by Nordhaus and Boyer (1999), Labriet and Loulou (2003) establish that cumulative damages in each region do not depend on the trajectory of emissions, but rather depend only on the cumulative global emissions. Further, the same research showed that the relationship may be considered linear in the realistic range of emissions that may occur in the next half century.[9] This result is captured by the set of damage equations (5.6):

$$D_i\left(\sum_{k=1}^{N} E_k\right) = a_i + b_i \times \left(\sum_{k=1}^{N} E_k\right), \tag{5.6}$$

where

$E_i =$ cumulative emissions of region i
$D_i(\cdot) =$ cumulative climate damage supported by region i
$a_i,\ b_i =$ slope and constant parameters of damage curve for region i.

As a result, cooperative and non-cooperative scenarios can be calculated as follows:

$$\text{Total Cost}_i = C_i(X_i, E_i) + D_i\left(\sum_k E_k\right) = C_i(X_i, E_i) + a_i \times \sum_k E_k + b_i.$$

Cooperation.

$$\text{Min} \sum_i \text{Total Cost}_i \tag{5.7}$$

Non-cooperation[10]**.**

$$\text{Min Total Cost}_i \equiv \text{Min}[C_i(X_i, E_i) + a_i \times E_i] \tag{5.8}$$

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[9] Without changing the qualitative results obtained by Labriet and Loulou (2003), the current work relies on slightly different assumptions: damages cumulated up to 2100, given the long-term climate effects of CO_2; damage discounting of 2%; and more rapid economic growth, reflecting MARKAL base-case scenario (IPCC-A1 family).

[10] Assuming that emissions are the only interdependency between regions. This means that international trade of energy commodities is not affected by climate policies, so that the cost of one region's strategy doesn't depend on other regions' abatement effort.

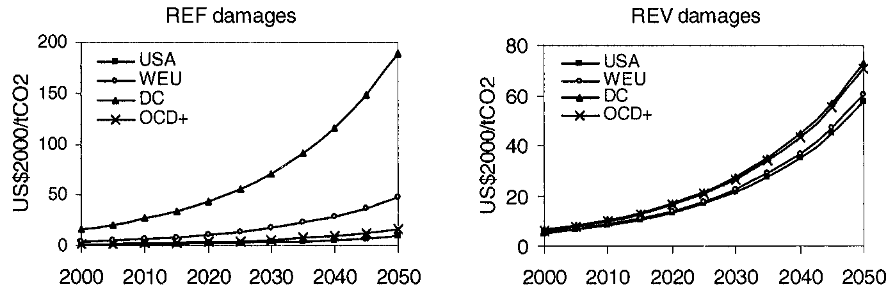

Figure 5.4. Regional climate damages represented as equivalent to a CO_2 tax.[a]

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[a] The 4 regions and REF/REV damages are defined in Section 4.4.

with

$C_i(\cdot)$ cost of the energy system of region i

X_i symbol of all the parameters influencing the cost of the energy system (investments, operation, etc.)

In other words, in a non-cooperative scenario, each country chooses its strategy by considering only that part of its own damage cost due to its own emissions (equation (5.8)). The emissions resulting from the energy decisions taken by other regions have no impact on decisions taken by region i, and damages supported by each region i due to emissions of other countries are added *ex-post* (out of MARKAL).

The non-cooperative case is modeled by adding to each region's objective function the appropriate regional linear damage term. The cooperation of a group of countries is modeled by replacing the regional damage factor by the sum of the regional factors of the cooperating countries. In MARKAL, this climate damage factor is equivalent to a carbon tax applied from 2000 to 2050 and adjusted according to the social discount rate (Figure 5.4). Of course, any cost-benefit conclusion that will be produced by this approach is fully dependent on the damage functions and the climate module assumptions.

4.3 Definition of non-cooperative behaviors

The computation of non-cooperative scenarios and transfers to guarantee the formation of the grand (world) coalition requires the definition of both the behaviour of regions that are not members of the cooperative coalition (equivalent to the definition of the threat in case of defection), and the information structure of the energy/environment decisions taken by the regions.

As regards the behaviour of outsiders, we adopt the γ-characteristic function proposed by Chander and Tulkens (1997): if a sub-coalition S forms, outsiders do not take particular coalitional actions against S (e.g., more emissions such as leakage) or in favour to S (e.g., less emissions if they form another coalition) but adopt their individually best reply strategies (individual Nash) and enjoy the cleaner environment induced by S's actions. This is also equivalent to saying that if a country or some countries deviate, the remaining players split up into singletons and play a Nash strategy. This standard assumption need not be uniformly verified in all instances, as we shall see in Section 4.5.

As regards the information, we assume an open-loop structure, where the regions cannot change their strategy in response to new information along the time path. This corresponds to negotiations that take place once: a binding agreement is signed in the first period and remains valid until the end of the horizon. Such an information structure may appear unrealistic, since it allows neither the renegotiation of ccoalitions nor the redistribution of transfers along time. It is nevertheless in tune with the perfect information and perfect foresight characteristics of the MARKAL model. It is also recognized that an open loop equilibrium is more easily calculated than a feedback one, and although less realistic and more optimistic in terms of abatement, it provides a good approximation of the feedback solution and remains appropriate to describe what would happen if an international binding treaty were reached (Germain and Van Ypersele, 1999).

Finally, the calculation of side-payments to guarantee the stable cooperation of all regions requires the computation of the gain for every possible coalition structure of the game. The computation of each coalition's gain corresponding to one world MARKAL run, we were led to regroup the fifteen regions into four groups, thus bringing the number of coalitional structures to a reasonable level (15). The four such groups are: USA, WEU, Developing countries (DC, formed by AFR, CSA, CHI, IND, MEX, MEA and ODA), and the rest of OECD countries and countries with an economy in transition (noted OCD+, formed by AUS, CAN, JPN, SKO, EEU and FSU). It is important to remember that every group now represents a pre-existing cooperating coalition of countries. Two consequences follow: first, no-cooperation with 4 regions is less so than with 15 regions. For example, the temperature increase reaches 1.43°C in 2050 with a four region model, against 1.55°C with a 15 region model (Figure 5.5). Second, because DC and OCD+ consist of a large number of different countries, it is rather difficult to outline a uniform strategy that would be optimal for all these countries. We are fully aware of the importance of the choice of these four regions on the

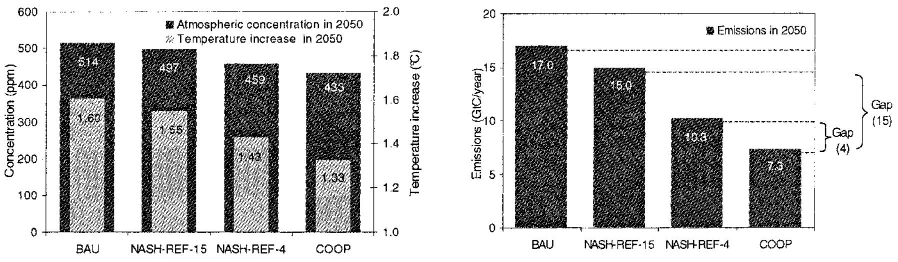

Figure 5.5. Emissions and temperature increase

results, and any other definition may be tested in further work, or better, a higher number of regions may be modeled if computational difficulties may be overcome.

4.4 Transfers

4.4.1 Sharing rules. The possibility of transfers between regions to ensure the stability of the cooperation of all regions is proposed by the cooperative branch of game-theory. It is a considered as a normative assumption, which has a sound justification in welfare economics, since it allows the satisfaction of both efficiency and equity: the regions undertaking emission reductions may differ from the regions that pay for abatement. However, the implementation of transfers in the real world is criticized, and governments are often reluctant to implement monetary transfers.[11] But transfers may also be translated into CO_2 permit allocations, technology transfers or issue-linkage (for the latter, see for example Carraro and Siniscalco, 1998). Thus, we don't claim that the calculated transfers may be directly implemented; they rather shed light on different possibilities for sharing the burden of reducing CO_2 among the different regions. This approach, based on a single economic criterion, might be considered as complementary to other approaches such as multicriterion analysis, as discussed in Section 3.

Transfers between regions are based on the sharing of the global (world) surplus of cooperation, represented by the socially optimum solution, over non-cooperative strategy, represented by the individual Nash solution. Several rules for allocating this gain are proposed by cooper-

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[11] The non-cooperative view of climate outcomes supports the more pessimistic view that any self-enforcing agreement will either be signed by very few countries, or, if signed by more countries, result in small emission reduction compared to the non-cooperative situation (see, e.g., Carraro and Siniscalco, 1998).

ative game theory and characterized by specific axiomatic properties. We computed four different transfer schemes, based respectively on the *Shapley value*[12] (Shapley, 1953), the *nucleolus*[13] (Schmeidler, 1969), the *transfer rule*[14] proposed by Germain et al. (1999) and finally, the *equalization of total abatement cost per GDP.*[15]

4.4.2 Results. Figure 5.5 provides the temperature increase (between 1.33°C and 1.60°C), the atmospheric concentration of CO_2 (433 to 514 ppm) and the emission level (7.3 to 17.0 GtC) in 2050 under the different scenarios. The reduction of cumulative emissions under the non-cooperative strategy represents only 21% of the reduction induced by the cooperation of all regions, which indicates that climate change reflects to a large extent, a collective problem. This result is not as dramatic when the number of players is reduced to 4, since even in the non-cooperative case, cooperation is implicitly assumed within each region (see Section 4.3).

Figure 5.6 and Table 5.10 show the allocation of the gain and the transfers between the four regions. The main results are as follows. First, all four solutions are in the γ-core[16] of the game, i.e., they all guarantee that every coalition enjoys at least as much as it can obtain on its own. Calculations also show that the core allows for a relatively large flexibility in the selection of allocations, so that the choice of the preferred allocation within the core may be adapted to other criteria emerging from international negotiations. Second, different regions may prefer different solutions. For example, the GTT rule favours regions with high climate damages, such as DC, while USA and OCD+ receive a much smaller part of the gain. Moreover, only DC prefers the SV to the NU solution, which reflects SV's property that regions that contribute much to the world CO_2 reduction and thus to the world gain

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[12] The SV attributes to every player i a payoff that reflects its average contribution to every possible sub-coalition.

[13] The NU yields an allocation such that the excesses of the coalitions are at the lexicographical minimum. It may be related to the Rawlsian philosophy that worse-off regions (those with the highest excesses) should be first satisfied

[14] The GTT transfer consists of adding a payment by each region equal to its gain of co-operation over no-cooperation (which may be positive or negative), and a payment to each country that consists in a fraction of the world gain proportional to the region's marginal climate damages.

[15] The TAC refers to the horizontal equity principle of comparable burdens. Total abatement cost is defined as the difference between the cost supported under cooperation and the cost supported under the individual NASH strategy, including both energy and damage costs.

[16] The γ-*core* is the set of all allocations (payoffs) that are not dominated for any sub-coalitions. Outsiders are considered to stick to their individual Nash strategy (Chander and Tulkens, 1997)

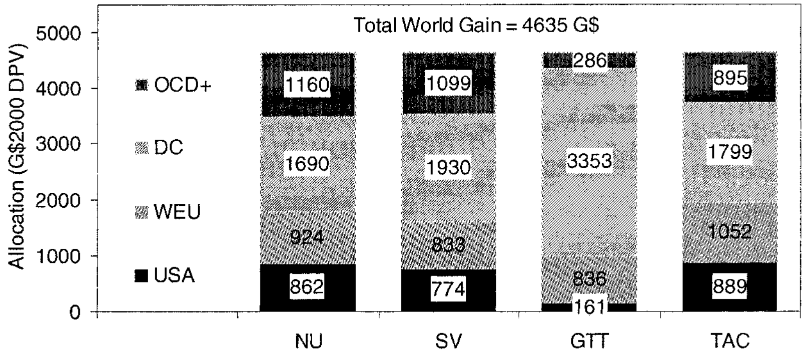

Figure 5.6. Allocation of the gain of cooperation over no-cooperation. Base case = A1B, Damages = Reference

Table 5.10. Transfers between regions (G$\$_{2000}$ DPV and % of total transfers). Base case = A1B, Damages = Reference

Rule	USA	WEU	DC	OCD+	Transfers
NU	1493 (48%)	−28 (−1%)	−3077 (−99%)	1612 (52%)	3106
SV	1405 (47%)	−119 (−4%)	−2837 (−96%)	1552 (52%)	2957
GTT	792 (52%)	−116 (−8%)	−1414 (−92%)	739 (48%)	1532
TAC	1520 (51%)	99 (3%)	−2968 (−100%)	1348 (45%)	2968

Remark. Negative values mean that the region is a donor

of cooperation, receive more. The other three regions prefer the allocation provided by NU, which favours regions less satisfied with world cooperation, i.e., regions with large abatement costs and/or low benefits from climate policies. Third, the TAC allocation guarantees that the total gain per GDP received by each region is equal to the world gain per GDP, which is 0.32%. TAC allocation favours WEU and DC, while OCD+ receives the smallest part of the world gain compared to the other allocations. This reflects the highest GDP of WEU and DC. Finally, the analysis of transfers shows that a donor can become a receiver in another context. For example, WEU is a receiver under TAC, while it contributes to payment in the other solutions. More globally, DC and, to a lesser extent, WEU, pay the USA and OCD+ to induce them to cooperate.

4.4.3 Sensitivity analyses.

Given the level of uncertainties, sensitivity analyses were conducted on the level of emissions in the base case (*FOS case*: lower share of nuclear and renewable in electricity generation, see Section 2) and on the regional distribution of climate damages (*REV case*: higher damages in industrialized countries and smaller damages in developing countries[17]). REV damages result in a more even distribution of damages among the four players (Figure 5.4).

We observe the following effects.

- First, the total gain of cooperation over no-cooperation is less under the REV case (4127 G$\$_{2000}$ DPV), and is higher under the more emitting FOS base case (7386 G$\$_{2000}$ DPV with REF damages, 5402 G$\$_{2000}$ DPV with REV damages). The latter confirms that the optimistic base case may underestimate the potential benefits of cooperation over no-cooperation (but despite higher world gains, larger reductions also imply more difficulties in reaching an agreement!). The former is explained by the fact that, when damages are more evenly spread, each region is likely to act at about the same level of effort on its own territory, and therefore there is less need for cooperation.
- Second, GTT's allocations are more evenly distributed among regions under the REV case, since damages are also more evenly distributed.
- Third, the total gain is equally shared among the four regions under FOS-REV, which means that no intermediate coalition has the power to impact the allocation of the world gain. In other words, more evenly distributed damages and higher emission reductions tend to favour more equal distribution of the world cooperation gain.
- Four, transfers are very sensitive to the level of regional climate damages, since under the REV cases, USA, WEU and OCD+ pay for DC accepting to cooperate, and the opposite occurs in the REF cases.
- Five, the possible variation of payoffs (not shown) is higher under REF than under REV scenarios; in other words, the more asymmetric the regions, the higher are free-ride incentives but also the flexibility in sharing the cost of cooperation.

We voluntarily did not try to explain all the differences or similarities between our numerical results and those provided by other studies since they reflect the high dependency of results on the mitigation costs and climate benefits specified in each model, as noted by most of authors.

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[17] Regions with low damages may be understood eitehr as regions with low real damages, or regions with a low political willingness to act, or not aware of, or paying little attention to climate damages.

Table 5.11. Sensitivity analyses: Transfers between regions (G$\$_{2000}$ DPV and % of total transfers)

Scenario	Rule	USA	WEU	DC	OCD+	Transfers
A1B-REV	NU	−424(−26%)	−769(−48%)	1591(100%)	−397(−24%)	1591
	SV	−522(−29%)	−846(−47%)	1785(100%)	−416(−23%)	1786
	GTT	−488(−29%)	−754(−46%)	1636(100%)	−393(−24%)	1637
	TAC	−605(−29%)	−767(−37%)	2083(100%)	−710(−34%)	2083
FOS-REF	NU	2378(50%)	−101(−2%)	−4629(−98%)	2353(50%)	4732
	SV	2231(50%)	−266(−6%)	−4210(−94%)	2245(50%)	4477
	GTT	1075(52%)	−112(−5%)	−1926(−94%)	962(47%)	2038
	TAC	2236(51%)	232 (5%)	−4401(−99%)	1932(44%)	4401
FOS-REV	NU	−355(−19%)	−843(−45%)	1837(100%)	−638(−35%)	1838
	SV	−482(−22%)	−974(−45%)	2162(100%)	−705(−33%)	2162
	GTT	−518(−26%)	−951(−47%)	1999(100%)	−530(−26%)	2000
	TAC	−670(−26%)	−967(−37%)	2584(100%)	−945(−36%)	2584

However, the general trends observed with our results are in agreement with those obtained in similar approaches such as Eyckmans and Tulkens (2003), Finus et al. (2003) and Van Steenberghe (2003).

4.5 Farsighted stability analysis without transfers

It is desirable to examine the stability of coalitions in the absence of transfers, in view of the potential difficulties of implementing them. To this end, the concept of farsighted stability analysis is seen as an attempt to account for the full consequences of some region's decision to defect from the grand coalition. Instead of assuming a fixed reaction from the rest of the coalition, it investigates all possible reactions by all remaining regions, and thus provides a more rigorous assessment of coalitional stability or unstability. Eyckmans (2001) demonstrates that introducing farsightedness restricts the number of credible deviations. For simplifying the analysis, we make the assumption that coalitions will not merge again after deviating (no multiple coalitions). The deviation by each region from the world coalition is analyzed by checking the costs incurred under each possible subsequent deviation. The analysis proves that no intermediate coalition is internally stable under A1B-REF, and the grand coalition is unstable: USA, for one, has an incentive to leave the grand coalition, and the final consequence is the individual Nash solution. Therefore, in this case, farsightedness does not increase the stability of any coalition.

Let us now assume that DC is out of the agreement (the remaining set of regions is representative of the Kyoto Protocol). The same analysis shows that the coalition formed by {WEU, OCD+} is internally stable, while USA remains a singleton. In this case however, the resulting world emission reduction is rather small (one fourth of the reduction of the world coalition), which is in agreement with studies using a non-cooperative framework (e.g., Carraro and Siniscalco, 1998; Hackl and Pruckner, 2002).

Farsighted analysis conducted assuming the A1B-REV scenario demonstrates that the intermediate coalition formed by USA and WEU is internally stable without transfers. Sensitivity analyses conducted with FOS base case show no different conclusion than with A1B.

4.6 Further work

An integrated version of MARKAL is proposed, and its application to climate change is discussed, based on the integrated assessment of climate decisions where the model balances the abatement costs and the climate damages and endogenously computes the resulting emissions. This project appears to be the first one of the sort applying game-theoretic principles to a large, detailed technology explicit model such as MARKAL.

Of course, as with any such analysis, the accuracy of our numerical results is limited by the extent to which the underlying assumptions (for example, climate damages) and model specifications are realistic, so that the real value of the paper lies more in the methodology and the general insights rather than precise numerical values.

Further work may take into account several of the caveats of the current work, such as: longer time horizon (possible with the advanced TIMES modeling framework), the addition of other greenhouse gases, the increase of the number of players (possible with an improved software for faster solving), the computation of feedback or also multi-coalition structure, the OPEC's behaviour, currently modeled as a cartel, or else the effect of climate policies on international trade.

5. Conclusion

In this expository article, the recent World MARKAL model was presented, and three types of application discussed. The model is suitable for classical cost-effectiveness analysis, but also for devising new permit allocation methods that rely on total abatement cost and have nice properties. Finally, a cost-benefit variant of the model, integrating damage costs due to climate change, is used to investigate cooperative and non-cooperative strategies addressing the threat of climate change. Such cost-benefit analyses were heretofore reserved to streamlined top-down models and their extension to detailed technology rich models represents a significant progress.

The research presented here may and will be extended in several ways: the model itself will be improved by extending its time horizon and enriching its database even further. Its oil price formation mechanism needs to be altered to better reflect the market power of the oil exporting cartel. Uncertainties that are inherent in several model areas (base case assumptions, damage functions, etc.) could be examined in the more rigorous framework of stochastic programming. The approach to the integration of damages followed in our research needs to be tested further if and when the horizon is extended, since the extended model will face larger emissions, concentrations, and temperature changes. Finally, in the case of non-cooperative strategies, parts of our analysis had to regroup regions into four groups; it would be desirable to increase the number of groups so as to make them more homogenous, but this will require surmounting the computational barrier.

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Chapter 6

A FUZZY METHODOLOGY FOR EVALUATING A MARKET OF TRADABLE CO_2-PERMITS

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Johan Springael

Abstract When developing a market of tradable CO_2-permits for achieving emission reductions, many badly known aspects must be accounted for. There are the landmarks to be imposed to the industry, the realistic schedules for their achievement, the potentials of different reduction technologies, the annual budgets that can be spent and last but not least the marginal pollution-abatement costs. In this methodological paper a simulation technique is developed to provide insight to public policy-makers into this complex matter. We propose to use fuzzy reasoning techniques to reconcile the diverging opinions of experts and to take into account the many uncertainties on marginal abatement costs.

1. Introduction — Objective of the paper

This paper presents a planning and control methodology for reducing pollution in a given country or region. More specifically, we concentrate on global pollution, like CO_2-emissions, for which perfect mixing over a given territory can be assumed. We do not enter into a specific discussion regarding a particular territory or a given case. Our purpose is entirely a methodological one, though we present a simplified didactic example in order to illustrate our approach.

Furthermore, we show that pollution permits have advantages with respect to other state-imposed pollution-reduction schemes, so that the quantitative elaboration focuses only on that instrument. In this paper, permits are distributed among polluters through a specialised trading market. We further assume that no banking of permits is possible, so that all of them are used in a given accounting year.

The basic question to be solved by the authorities to have a market of this type functioning is twofold:

- How many permits should be fed onto the market each year, and how long is the horizon for planning? It is obvious that in principle the number of permits released to the market must decline over time, given the pollution-abatement objectives;
- What are the priorities to be given to some abatement technologies, perhaps with the direct or indirect support of the authorities, e.g., subsidies, green certificates for promoting renewable energies (Kunsch et al., 2002), etc.?

Elaborating scenarios on the basis of expert opinions and some plausibility factors can ease the answers to those questions. The paper presents an approach, based on fuzzy-reasoning to support this process. The deliverable is a 5-year rolling horizon planning destined to the authorities for implementation and control.

This chapter is constructed as follows after this first introductory section. In the second section a brief overview is given on pollution control instruments. We set out why pollution permits have been adopted for developing the proposed methodology rather than other instruments. In the third section we present the elements of a deterministic permit model. The fourth section discusses the planning needs of the control authorities in more details. In the fifth section we explain how uncertainties can be taken into account in these plans. Fuzzy-reasoning techniques are introduced by describing how they are used to take into account several different opinions of experts on evolution scenarios. In the sixth section a simple didactic example on CO_2-permits is elaborated. Finally, we end with some conclusions in the last section.

2. Usual pollution-control instruments

The control of pollution emissions is possible according to several regimes:

(1) Command-and-Control;
(2) Tax or subsidies;
(3) Licences or marketable emission permits.

A Command-and-Control regime consists in imposing limits on emissions by means of regulations imposed by a state-owned regulating body. We will not further discuss here this possibility.

A tax regime is also a pure state instrument. A tax per unit of emitted pollutant of a given kind, e.g., CO_2 or CO_2-equivalent, is charged to the

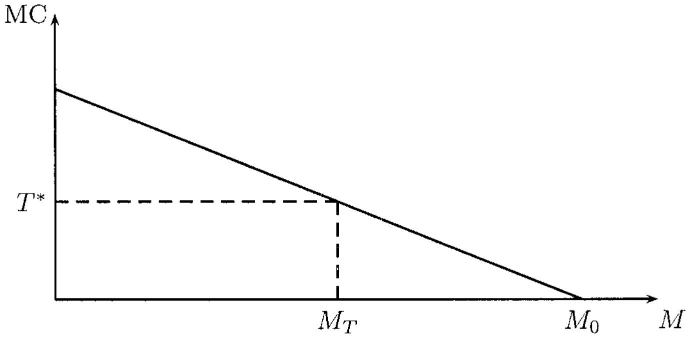


Figure 6.1. A handbook representation of the marginal abatement cost (MC) as a function of the pollution level (M). T^* represents the tax level which corresponds to an optimal emission level M_T. The zero-abatement level is given by M_0.

polluters (see Kunsch et al. (1999) for an example). The principle is shown in Figure 6.1. It is assumed that a curve (here represented by a straight line for simplicity), representing the marginal abatement cost (MC) per unit of emission as a function of the total emission level of the specific pollutant (M), is perfectly known.

In the classical handbook representation like Hanley et al. (1997); Perman et al. (2003) this curve would be decreasing to the maximum emission level per time unit (M_0), because of the law of diminishing return. M_0 corresponds to the situation where no abatement measure is taken. A rational polluter would decrease the emission level from M_0 to M_T in order to achieve the economic optimum (see Perman et al., 2003 for a formal proof). The polluter has to pay the tax amount indicated by the rectangular surface. At equilibrium the total emission will be calculated as follows, given a tax level T^*, and inverting the function MC(M):

$$M_T = \mathrm{MC}^{-1}(M) \tag{6.1}$$

A subsidy regime, not further discussed here, would be a mirror image of the tax regime: it encourages abatement measures by a positive payment from the state regulator to the polluter, up to an equilibrium point between marginal cost and per-unit subsidy.

A scheme of marketable emission permits functions on the basis of the "cap-and-trade" principle. This means that each year the regulatory authority caps the yearly emission level which is allowed by issuing the corresponding number of permits. The idea is to have year after year a decline in this emission level. Permits can be traded on a specialised permit market between the users, who are the potential polluters. Each permit has a nominal value, expressed in units of pollutant emission per year, e.g., 1 metric ton CO_2/year. This gives the right to its possessor to emit this quantity during the year. As a consequence, a given polluting operator receives the permission to emit an annual total quantity given by the total number of permits he has in hands, times the facial value of each permit, in general expressed in metric tons of pollutants per year which we will indicate in the following as [tP/year]. There are several possible variants for designing the specialised trading market for permits according to IEA (2001). In order to keep things simple for our elaboration, simple assumptions were adopted:

- At beginning of the current year, the regulatory authority issues the permits in a given quantity [tP/year]. There are allocated to polluting operators through an auction system. Each permit is labelled with the indication of its emission year;
- An equilibrium price between the fixed supply decided by the state and the demand of operators is formed in this auction process;
- The validity of the permit is limited to its year of emission, with other words no "banking" is allowed;
- At any time operators can exchange, i.e., buy and sell permits on the market, at the equilibrium price.

(Extensions to more complex or realistic rules like those described in IEA (2001) would be easy to achieve, but they would not serve our exposition of the methodology).

Each year the equilibrium situation represented in Figure 6.2 will be obtained. As in the tax scheme, it is assumed that the curve of marginal abatement cost (MC), as a function of the emission level M, is perfectly known. It is assumed that total permitted emission in this current year is given by M_p.

Comparing this drawing to Figure 6.1 and equation (6.1), it can be remarked that the situation is now inverted: the final price is calculated by using the function MC(M), the maximum emission M_p now being given, so that the price P^* can be directly computed:

$$P^* = \mathrm{MC}(M_p) \tag{6.2}$$

Note that both tax level and permit price are equal to the marginal abatement cost. Thus the following property holds:

$$M_T = M_p \iff T^* = P^* \tag{6.3}$$

The difference between two schemes is that the regulator has to define the correct tax level in order to achieve the abatement objective, while the price of permits results from the market, this objective being given. In practice this handbook presentation is too simplified to represent reality for the following four reasons:

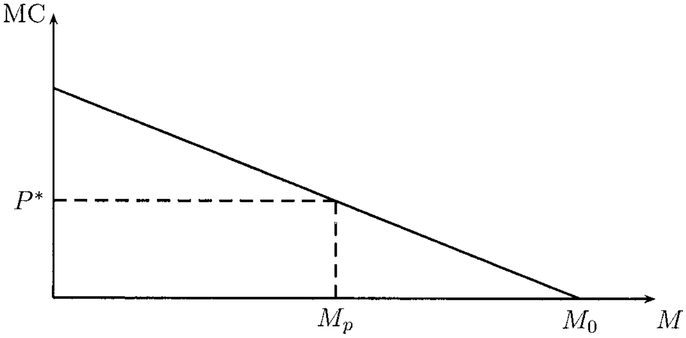


Figure 6.2. A handbook representation of the action of marketable permits at the maximum permitted emission level M_p. MC is the marginal abatement cost as a function of the pollution level (M). P^* represents the equilibrium permit price. The zero-abatement level is given by M_0.

(a) Different polluters have different marginal abatement cost given by different MC's;

(b) For some polluters the law of diminishing return, resulting in downward MC(M) functions may not be verified: some portions of the curve may be increasing as a function of M, or have non-monotonous shapes;

(c) This presentation is entirely static: in practice the goals $M_T = M_p$ are dynamic, i.e., changing downward each year. The pace of these dynamic changes is dependent on different parameters. Total available budgets for adapting the abatement techniques, and timelags in making these techniques operational are to be taken into consideration when adapting the abatement goals, year after year;

(d) Last but not least, MC-curves are generally not known with great accuracy; there are different possible scenarios for the technology evolution, or varying opinions about cost paths for achieving this evolution.

Regarding the uncertainty aspects addressed in topic (d), tax and permit schemes behave very differently, despite the similarity between eqs. (6.1) and (6.2) in the deterministic case:

- A tax scheme operates on a cost basis, without precise consideration of the abatement goal. Assume in Figure 6.1 that the MC-curve is displaced horizontally to the right because of uncertainties. The equilibrium emission level M_T will be translated to the right in the same way, giving a different policy result.

- A permit scheme operates on a emission-level basis, keeping a well-defined objective M_p. Assume in Figure 6.2 that the MC-curve is also displaced to the right as before. The abatement goal being fixed by construction, induces an increase of the permit price in a way depending on the translation and the slope of the MC-curve.

This basic difference between both schemes implies that permits are reliable, i.e., they possess the dependability property elaborated in Perman et al. (2003). Taxes are by contrast not dependable, when it comes to achieving a well-defining abatement goal. Also they are less flexible than permits: it is generally admitted that a change of a tax level is less easily accepted, because it is felt as being arbitrary, compared to an adjustment in price resulting from market forces.

Permit schemes are mixed instruments, as they require both state and market interventions. They are more flexible than pure state instruments. In this respect Tax and Command-and-Control schemes are rather akin. This is the main reason why our methodology has been developed for permit schemes.

3. A deterministic dynamic permit model

Before explaining how to address uncertainties, we present a deterministic model taking into account the important practical aspects a) to d) discussed in Section 2. The handbook approach of permit schemes can be made more realistic by considering the following improvements:

- The policy-makers scrutinising the abatement potential are not directly interested in the many individual operators, and their corresponding MC-curves, present on the permit market. Rather, quite few MC-curves of interest can be identified. They are common to similar techniques or technologies used by these operators for abating pollutant emissions;
- The MC-curves of interest can be transformed, so that they have a common origin. This is easily done by replacing the static pollution level axis M in Figure 6.2 by the dynamic pollution-abatement level (AM). Along this axis the current abatement quantities are represented and assumed to be vanishing at the start of the dynamic model (i.e., in $t = 0$). This gives a common origin in the frame in which MC-curves of interest for decision-makers are represented;
- Having given a common framework to the MC-curves, we can generalise their shapes which can be any function of the abatement quantities computed from the initial emission level in $t = 0$. On the right side each MC-curve i is bounded by the abatement limit,

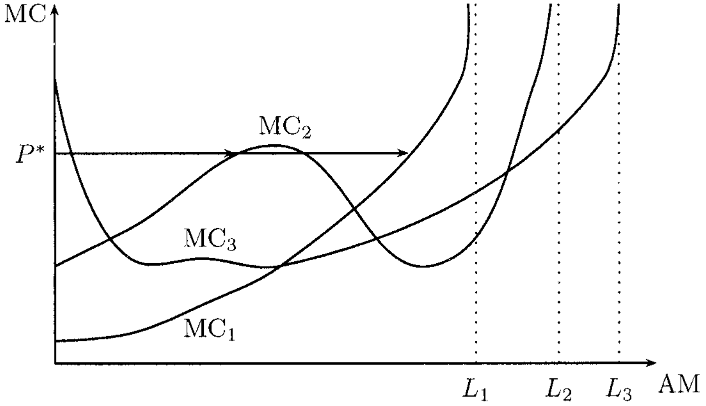


Figure 6.3. Stylised representation of three MC-curves, indicating the corresponding boundaries (L_i, $i = 1, \ldots, 3$). The total abatement obtained for a price P^*, starting from an initial goal AM $= 0$, is obtained by taking the horizontal sum of the two abatements of these techniques which are active for this price, e.g., techniques 1 and 2 for the indicated value P^*. (Note that technique 3 is not active for the price value P^*, since its initial marginal cost is larger than P^*).

equal to the value L_i in [tP/year]. A way of representing these limits is to have the curve i becoming asymptotically vertical at L_i. Figure 6.3 shows a stylised representation of three such curves (MC_1 to MC_3).

The dynamic evolution of abatements for the different techniques, starting at $t = 0$, and from an initial goal AM increasing from zero, can be easily calculated. Consider the simple example in Figure 6.3. Call $AM_i(t)$, the three abatement values as a function of time t with $AM_i(0) = 0$ for $i = 1, \ldots, 3$, $MC_i(t) = MC_i[AM_i(t)]$ the corresponding current value of the three marginal costs, $MC_i(0)$, $i = 1, \ldots, 3$ the initial values of the three marginal costs before any abatement, and $P(t)$ the current permit price.

At any time t we have that

$$P(t) = \min_i \left[MC_i \left(AM_i(t) \right) \right] \tag{6.4}$$

$$AM(t) = \sum_i AM_i(t) \tag{6.5}$$

Thus, in the particular case shown in Figure 6.3, we can follow the first stages in the evolution:$P(t = 0) = MC_1(0)$, as this value is the smallest one;

For $P(t) < \mathrm{MC}_2(0)$**:**

$$\begin{cases} \mathrm{AM}(t) = \mathrm{AM}_1(t) \\ P(t) = \mathrm{MC}_1[\mathrm{AM}_1(t)] \end{cases} \tag{6.6}$$

For $\mathrm{MC}_1(t) = \mathrm{MC}_2(t) < \mathrm{MC}_3(0)$**:**

$$\begin{cases} \mathrm{AM}(t) = \mathrm{AM}_1(t) + \mathrm{AM}_2(t) \\ P(t) = \mathrm{MC}_1[\mathrm{AM}_1(t)] = \mathrm{MC}_2[\mathrm{AM}_2(t)] \end{cases} \tag{6.7}$$

For $t \geqslant t_1$ **with** $P(t_1) = \mathrm{MC}_3(0)$ **and** $d\,\mathrm{AM}_3(t)/dt \leqslant 0$**:**

$$\begin{cases} \mathrm{AM}(t) = \mathrm{AM}_1(t) + \mathrm{AM}_2(t) + \mathrm{AM}_3(t) \\ P(t) = \mathrm{MC}_3[\mathrm{AM}_3(t)] \end{cases} \tag{6.8}$$

For $t > t_1$ and for as long as the marginal cost MC_3 remains decreasing (i.e., its first derivative $d\,\mathrm{AM}_3\,/dt < 0$), it dictates the price and the further abatement, because only the third technology is active at this stage. The two first technologies are dormant: they remain "stuck" at levels $\mathrm{AM}_1(t_1)$ and $\mathrm{AM}_2(t_1)$ respectively, until AM_3 increases again up to the price level in t_1, then they start again being active, and the following stage can start, etc.

As it is well visible from Figure 6.3 and eqs. (6.6) and (6.7), the active abatement quantities are adding horizontally at a given price level. It is shown in Perman et al. (2003) that this situation corresponds to the cost optimum. All active marginal costs of technologies are equal to the permit price, under the condition that they are active, i.e., that they contribute to the abatement. In the example above the dormant technologies 1 and 2 in eq. (6.8) are stuck at the t_1-level; the price is following the third marginal cost MC_3, which is active.

More generally the complete system evolution over time can be computed in two steps:

1 Compute first the relative contribution of each active MC-curve in the abatement increase;

2 Determine then the current total abatement goal $\mathrm{AM}(t)$, compatible with the constraints, as the sum of the partial abatements.

For performing the first step, consider at current time t the imposed goal $\mathrm{AM}(t)$, and $i = 1, \ldots, I$ active MC-curves. The term "active" has the meaning which has been shortly explained. The marginal costs of the active MC-curves in t, all equal to the permit price $P(t)$, are given by eq. (6.4) for the given set of i-values.

Impose now a slight value increase in the abatement goal by the small quantity $\Delta\,\mathrm{AM}$. Under this change the I marginal costs will change at first order as follows:

$$\Delta\,\mathrm{MC}_i = \frac{d\,\mathrm{MC}_i}{dt}\Delta\,\mathrm{AM}_i = d_i\Delta\,\mathrm{AM}_i, \quad i = 1,\dots,I \tag{6.9}$$

with $\Delta\,\mathrm{MC}_i = \Delta P$, $\forall i = 1,\dots,I$ where d_i represents the first derivative of MC_i; ΔP the change in permit price caused by the change in the abatement goal. Equation (6.9) results from the equality of all active MC with the permit price.

Thus for all pairs i, j, and any active value on the MC-curve, one obtains

$$\frac{\Delta\,\mathrm{AM}_i}{\Delta\,\mathrm{AM}_j} = \frac{d_j}{d_i}, \quad \forall i,j = 1,\dots,I \tag{6.10}$$

and therefore as $\Delta\,\mathrm{AM} \to 0$ at time t:

$$\Delta AM_i(t) = \frac{1/d_i(t)}{\sum_{i=1}^{I} 1/d_j(t)}\Delta\,\mathrm{AM} = r_i(t)\Delta\,\mathrm{AM}, \quad i = 1,\dots,I \tag{6.11}$$

Hence, the inverse slope of any MC-curve, which is of course equal to its derivative at the current abatement value at time t, determines the relative abatement of each active technology for a small increase of the goal.

The goal itself, represented by $\mathrm{AM}(t)$ can be computed in a second step, by considering the prevailing constraints under which all technologies can develop. Usually the budget for R&D and technological development will be the key variable to be considered.

Assume a total yearly budget(t), equal to $B(t)$, and expressed in [CUR/year] is available (CUR stays for currency units). First we consider that it has to be shared by all competing technologies.

Within a small time interval $[t, t + \Delta t]$ the budget spending is given by:

$$B(t)\Delta t = P(t)\Delta\,\mathrm{AM}(t) \tag{6.12}$$

leading for $\Delta t \to 0$ to

$$\frac{d\,\mathrm{AM}}{dt} = \frac{B}{P} \tag{6.13}$$

In a second more sophisticated, approach the total budget is composed of individual budgets for the I active technologies at time t:

$$B(t) = \sum_{i=1}^{I} B_i(t) \tag{6.14}$$

Consider j such that

$$\frac{B_j}{r_j} = \min_{i=1,\ldots,I}\left[\frac{B_i}{r_i}\right] \tag{6.15}$$

For this active component j, one may write, using eq. (6.13) and the definition of r_j expressed by rel. (6.11):

$$\frac{d\,\mathrm{AM}_j}{dt} = r_j\frac{d\,\mathrm{AM}}{dt} = \frac{B_j}{P} \Longrightarrow \frac{d\,\mathrm{AM}}{dt} = \frac{B_j}{Pr_j} \leqslant \frac{B_i}{Pr_i}, \forall i = 1,\ldots,I \tag{6.16}$$

where all variables take their current values at time t. This relation applies because the price P is the same for all active technologies.

4. The needs of the control authorities

The planning of the pollution control in a given country or political region requires interventions of an external regulator, which is in general owned by the central state and its government. This statement is of course mainly correct for Command-and-Control and tax schemes. We have shown in Section 2 that both schemes are not very dependable or flexible in the presence of uncertainties. Tax schemes for example (see Figure 6.1) bring unsatisfactory adjustment with respect to the abatement goal, when marginal-cost curves are imperfectly known. Permit schemes are by contrast reflecting uncertainties in the MC-curves in the price level to be paid by producers who are short of permits with respect to the abatement goal imposed by the authorities (see Figure 6.3). This is not a too serious drawback, however. Assuming that the penalty level imposed to the trespassers who do not respect the goal is rather large, the efficiency of the permit will not be very effected by this uncertainty. This is because rational operators will in any case pay a higher price for the missing permits, rather than being willing to pay a significantly larger penalty.

Those considerations strengthen our preference for modelling permits rather than abatement taxes with the present model. The latter scheme is entirely a state instrument. The former scheme gives a hybrid instrument, i.e., combining interventions from both the state-owned regulator and the market of permits. Although the market will dictate the eventual price, the regulator has to determine an abatement objective and its dynamic realisation path. Nowadays international agreements, like the Kyoto Protocol (1997), are setting external goals and their achievement periods. These objectives could prove to be largely unachievable, in case they do not correspond to realistic achievements of available technologies and their pace of future development in future years. Kunsch et al. (2004) have shown that the reduction objectives must be directly driven from the possible achievements and not the reverse. In a more favourable case the chosen objectives may severely underestimate the real abatement potential, and this can also be a source of trouble in case the pace of reduction is too slow with respect to environmental damages or risks.

It is why authorities need more details about the MC-curves, in order to be able to design a coherent and efficient strategic plan on how much pollution emissions are permitted over a medium-term horizon, over five years. Having that the resulting evolution of the permitted total emission over time $\mathrm{AM}(t)$ is also available.

It is the purpose of our approach to assist and formalise the preparation of this strategic plan, given that are many different opinions about the shape of the MC-curves as a function of the abatement levels. Large uncertainties exist for their interpolation over the future even for a limited number of years.

What can be used here is scenario analysis and a rolling plane horizon of five years, i.e., with updates to be made yearly in the projections and paths for the five coming years.

Classical scenario or sensitivity analysis is not entirely satisfactory, however. It provides ranges of values, elaborating on optimistic, average, or pessimistic forecasts related to the evolution of the output variables in the model. The industry is eager for the sake of efficient medium-term planning to be knowledgeable of well-defined objectives for a sufficient number of years, probably at least five. But collapsing many scenarios into one requires an additional knowledge of a priori occurrence probabilities, which is almost never present.

Therefore other aggregation techniques for scenarios and opinions must be sought for. In the next section we propose to use fuzzy-reasoning techniques. To that purpose the opinions of qualified experts regarding the MC-curves are collected and processed.

These opinions are the equivalent of a range of scenarios, but there is no need for a priori subjective probabilities, like in the Bayesian approach. It is only assumed that a scoring of the experts on a $[0, 1]$ scale is available. It should be derived from their experience in the abatement technologies, their past performances in assessing the evolution, etc. It is beyond the scope of this paper to discuss how the scoring of experts is made. The readers are referred to the existing literature on this aspect like described in Meyer and Booker (2001). The scoring expresses the credibility that can be given to opinions. It can be decided to eliminate less useful opinions, i.e., scenarios, by using cut-off rules, for example eliminating all opinions that score less than 0.25, etc. The same approach can of course be used by giving directly credibility scores to scenarios for available historical data, but this seem to be a more perilous attempt. The Past is only a poor predictor of the Future. It is thus better to use multiple human opinions as basic inputs.

Scores of experts are NOT simply used as weights. A more sophisticated and less arbitrary aggregation techniques than weighed sum must be developed. It is again based on a fuzzy-reasoning we now introduce.

5. A fuzzy-reasoning approach to aggregate expert opinions on MC-curves

In Kunsch and Fortemps (2002), one of the authors has discussed approaches in fuzzy reasoning to aggregate expert opinions. We use some explanatory material given in this paper to introduce this technique.

Fuzzy Logic (FL) is a mathematical technique to assist decisions on the basis of rather vague statements and logical implications between variables. FL is close to the natural language, this is why some people have called it "computation with words." It is very useful in many technical and economic applications in which imprecise and relatively vague judgements of experts have to be accounted for in a quantitative way as explained for business applications in Cox (1995).

The first step in the approach is called "Fuzzification" The basic ingredients of *fuzzification* are (1) "membership functions" to represent the range of possible values of a vague or imprecisely known variable ("fuzzy variable" as opposed to "crisp variable"), and (2) "fuzzy rules." The latter relate fuzzy variables, in the antecedent of the rule on its input side, to draw some conclusions on the final results, in the consequent of the rule.

(1) A "Membership function" (m.f.) provides a possibility measure, called "membership grade" (m.g.) for some affirmation. For example, the m.f. "MIDDLE-AGED" for a human being might be represented by a triangular m.f. as follows: the m.g. is 0 at 30 years (y), it peaks at 1 at 45 y, and it comes down to 0 at 60 y. This triangular m.f. is represented by the triple (30 y; 45 y; 60 y). In the same context other lifetimes could be represented, e.g., "CHILD," "YOUNG, "OLD." The interval of variation of the fuzzy variable is called the universe of discourse, in the given example for life-ages, it could be in the interval $[0, 100]$ (years). The first part of fuzzification consists in translating imprecise variables into a fuzzy variable, represented by a m.f., e.g., using four m.f.'s describing different ages of life. Note that m.f.'s are different from probability distributions. For example, the total surface under-

neath any m.f. is not normalised to 1. They are defined in the framework of possibility distributions.

(2) A mapping between fuzzy variables is made possible by using "fuzzy rules," which are the second part of fuzzification. In the given example, rules connecting the life-ages to the degrees of experience could be imagined:
   (a) If "AGE" is "YOUNG" then "EXPERIENCE" is "LIMITED"
   (b) If "AGE" is "MIDDLE-AGED" then "EXPERIENCE" is "APPRECIABLE"

etc.

In this 1-input, 1-output fuzzy system, the four life-ages ("CHILD," "YOUNG," "MIDDLE-AGED," and "OLD") would be represented by triangular m.f.'s and the experience levels by corresponding four trapezoidal m.f.'s (e.g., "VANISHING," "LIMITED," "APPRECIABLE," "IMPORTANT").

The second step is called "Implication." An implication operator defines the m.f.'s of consequents, given some value of the antecedent and applying the logical fuzzy rules. The "min" implication operator, corresponding to a logical "AND" is commonly used in control systems of the Mandami or Sugeno type as explained in Passino and Yurkovich (1998).

For example, assuming that u is the m.g. of the input "YOUNG" to the rule (a), and Y is the m.f. representing "LIMITED", the "min" implication operator will give as output for the rule a truncated trapezoidal m.f. of height $\min(u, Y)$.

The third step in fuzzy reasoning is called "Aggregation." In aggregation, the consequents of all partial rules are aggregated using an additional aggregation operator, e.g., the "max" operator corresponding to a logical "OR." This operation will result in a composite m.f.

The fourth and final step is called "Defuzzification." Defuzzification consists in deriving a unique final answer from the composite m.f. obtained in the aggregation. Different defuzzification operators are used. The most common one is "centroid" which comes to calculating the center-of-gravity of the aggregated m.f.

The same sequence of four fuzzy-reasoning steps, "fuzzification," "implication," "aggregation," "defuzzification" will be used in the particular abatement problem we have here. To be more practical, we consider the example of CO_2-abatement technologies, we will further develop in Section 6 with the didactic example.

Assume that there are n experts, and that their credibility factors (C_i, $i = 1, \ldots, n$) are given on a $[0, 1]$ scale.

To follow the described sequence in fuzzy reasoning we start with "Fuzzification." It has to be assumed here that the universe of discourse for representing CO_2-abatement levels can be agreed upon by all experts. In our example, this would result in $L = 5$ levels, each represented by a triangular m.f. $u_l^{(k)}$, for each technology $k = 1, \ldots, K$:

$$(u_l^{(k)},\ l = 1, \ldots, L : \text{vanishing, small, medium, large, absolute}) \quad (6.17)$$

These five m.f.'s appear on the left of Figure 6.4 which we will discuss in detail.

Each expert makes a mapping of these levels to the levels of marginal costs for a particular abatement technology $k = 1, \ldots, K$. Each mapping generates a set of $L = 5$ membership functions, each representing an opinion O on the marginal cost, expressed in [CUR/(ton CO_2/Month)]. This provides in all $n * K * L$ expert opinions, as follows:

$$\begin{aligned} &O(i = 1, \ldots, n; k = 1, \ldots, K; l = 1, \ldots, L; \text{Opinion of } n \text{ experts} \\ &\qquad \text{on the MC}(l, k) \text{ for } l = 1, \ldots, L\ \mathrm{CO_2}\text{-levels}) = O(i, k, l) \end{aligned} \quad (6.18)$$

which correspond to the set of $n * K * L$ partial rules, considering all K technologies:

$$\begin{aligned} &\text{IF } \mathrm{CO_2}\text{-emission level(technology } k) \text{ is } \mathrm{CO_2}(k, l) \text{ AND} \\ &\qquad \text{Expert}(i) \text{ is } C_i \text{ THEN MC}(l, k) \text{ IS } O(i, k, l) \end{aligned} \quad (6.19)$$

Equations (6.17) to (6.19) complete the "fuzzification" step.

What we are now up to is to perform the second step, i.e., the "Implication." It consists in calculating the m.f. of the conclusion of each partial rule.

To make things simple we use here the so-called Mamdani–Sugeno implication explained in Passino and Yurkovich (1998). This implication, say R_{MS}, is the conjunction with the logical "AND," represented by the simple "min" operator between the inputs and the output of the rule. Calling $\mu_{il}^{(k)}$ the m.f. of the conclusion of the partial rule (i, k, l), established by expert i for the lth level of pollution in technology k, we may write:

$$\mu_{il}^{(k)} = R_{\mathrm{MS}}(u_{il}^{(k)}, v_{il}^{(k)}) = \min(u_{il}^{(k)}, v_{il}^{(k)}) \quad (6.20)$$

where $u_{il}^{(k)}$ represents the m.g. of the antecedent to the rule (i, k, l) in eq. (6.19) and $v_{il}^{(k)}$ represents the m.f. of the opinion $O(i, k, l)$ coming in the conclusion of the rule in this equation.

The antecedent of the rule (i, k, l) in eq. (6.19) is itself the conjunction of two inputs. The first one on the left, represents the m.g. of the lth

CO_2-level (e.g., for $CO_2(k = 1, l = 3)$, $u_3^{(1)} = 0.3$), the second one on the right represents the credibility C_i of the ith expert (e.g., $C_1 = 0.8$). Because this is a conjunction, the simple min-operator applied to these two values can be used: both values are by definition in the interval $[0, 1]$.

In this case we obtain for $u_{il}^{(k)}$ defined in eq. (6.20)

$$u_{il}^{(k)} = \min(u_l^{(k)}, C_i) \tag{6.21}$$

(in this example $u_{13}^{(1)} = \min(0.3; 0.8) = 0.3$, for the CO_2-level $l = 3$ ("medium") in the judgement of the expert $i = 1$ on technology $k = 1$).

Note from (6.21) that an expert with a vanishing credibility will have a vanishing m.f. for all opinions he expresses, by application of the implication (6.20). This expert will thus be ignored in the further treatment. If all experts have a vanishing credibility, no conclusion can be drawn at all from fuzzy reasoning.

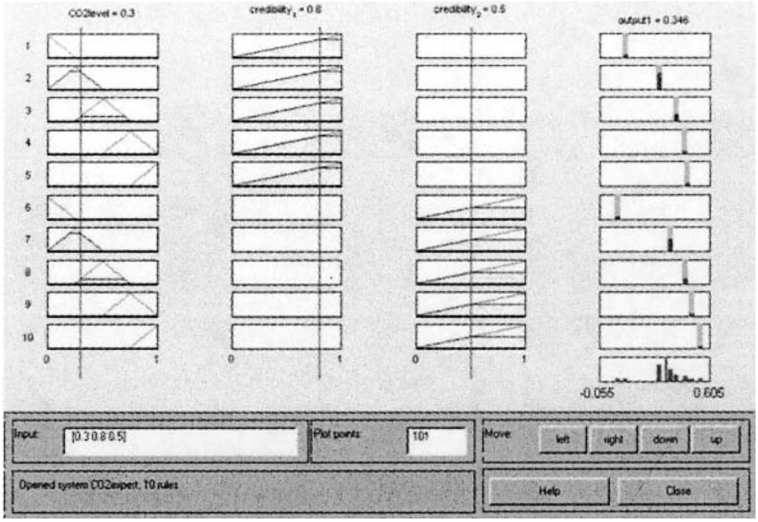
For the m.f. $v_{il}^{(k)}$, defined in (6.20), it is sufficient to adopt as a single value of the marginal cost (singleton with m.g. = 1). This is the special form of the Mamdani – Sugeno inference introduced by Sugeno, and thus called more simply Sugeno implication (see Passino and Yurkovich, 1998). It is very useful to represent arbitrary functions in control theory, like here the MC-curves, the shape of which can be complicated. The singleton receives a m.g. = 1, so that eq. (6.20) immediately simplifies to:

$$\mu_{il}^{(k)} = u_{il}^{(k)} \tag{6.22}$$

In the Sugeno implication the conclusion of each rule thus receives the same m.g. as the antecedent of the rule.

This process is well visible on the right of Figure 6.4 representing the full fuzzy-reasoning process. Each window represents a rule. For simplification, two experts are considered ($n = 2$) and one technology ($K = 1$). Because of $L = 5$, there are 10 rules, each represented in a separate window. The m.g. of the combined inputs is calculated by means of the conjunction operator "min" on the left. The m.f.'s of the conclusions on the right reduce to singletons which receive the same m.g. as the combined inputs of the applicable rule.

The next step is "Aggregation." The conclusions of all partial rules (i, l) relative to all experts and all CO_2-levels are combined in order to obtain a global m.f. for a given (k) technology. This is done by using the logical "OR," represented by the simple "max" operator applied to all outputs of the individual rules. In the Sugeno inference this is particularly simple, because the conclusion of each rule is a singleton



Input: [0.3 0.8 0.5]

Plot points: 101

Opened system CO2expert, 10 rules

Figure 6.4. The fuzzy-reasoning steps for $k = 1$ and $n = 2$ are from left to right: "Fuzzification" of both inputs; "Implication" of the partial Sugeno-rules, "Aggregation" of the partial conclusions of rules to a global m.f. (right-bottom window), and "Defuzzification" of the global m.f. to a unique output through the center-of-gravity methodology (output1 = 0.346) (arbitrary scales and units). (Calculations are made with Fuzzy Toolbox of MATLAB®, 2001)

the m.g. of which has just been calculated in the previous implication step. The global aggregated m.f. for each technology $k = 1, \dots, K$ has thus $n * L$ components given by

$$\text{m.g.}^{(k)} = \{u_{il}^{(k)}; = 1, \dots, n; l = 1, \dots, L\} \tag{6.23}$$

The lowest frame on the right of Figure 6.4 represents the set of values representing the global m.f. of technology $k = 1$ aggregating all partial rules. In the general case with $K > 1$, this step is performed separately for each technology.

The final step in the fuzzy-reasoning schemes is "Defuzzification" of the global m.f.'s for each $k = 1, \dots, K$. It consists in calculating a unique "crisp" value from the global m.f. In this particular case the center-of-gravity (COG) is the most adapted approach to obtain this value. This is expressed as follows for each set of inputs (current CO_2-level and credibility factors):

$$\begin{aligned} &\text{COG}^{(k)}[\text{CO}_2\text{-emission level}; C_i, i = 1, \dots, n] \\ &\qquad = \frac{\sum_{i=1}^{n} \sum_{l=1}^{L} O(i,k,l) u_{il}^{(k)}}{\sum_{i=1}^{n} \sum_{l=1}^{L} u_{il}^{(k)}} \end{aligned} \tag{6.24}$$

The calculation of the COG for $k = 1$ is shown in the lowermost window on the left of Figure 6.4.

Note that fuzzy-inference systems (FIS) like just described have the property of being universal approximators for any nonlinear function. In the case of only one expert ($n = 1$), eq. (6.24) is shown to interpolate the MC-curve of a specific technology k between the anchor values, i.e., the opinions this expert has given for the L CO_2-levels. For a very complex MC-function the number of anchor points and thus the number of levels L and of rules may have to be kept quite large, in order to stick as closely as possible to the expected MC-curve. In this case $n = 1$, which corresponds to the absence of uncertainties on the MC-curves, limited information is brought by the use of fuzzy reasoning. The most direct way is to use the suitably interpolated MC-curve.

The added value of fuzzy reasoning comes with the existence of different opinions. Formula (6.24) then does not only interpolate between anchor points. In addition, it provides an easy approach for aggregating all opinions to one global result, taking into account the credibility grade of each opinion. We remark that regarding the credibility grades of experts, this approach is far less arbitrary than a simple additive weighing technique for combining opinions! The sum of credibility factors is not normalised. If necessary, additional stochastic risk analysis can be added to this simulation model, e.g., as follows:

- The budgets attached to one or to all technologies as explained in eqs. (6.13) or (6.16) can be handled as random variables with some given probability distribution;
- The credibility factors of experts (or scenarios) can also be handled as random variables within some intervals. For example the credibility of the ith expert can be assessed as being a normal distribution with some mean value and standard deviation (it must be truncated to avoid negative values or values larger than one).

Simulation codes can generate results in the form of probability distributions of costs or abatement quantities evidencing percentiles.

We think, however, that such refinements will have limited added values in terms of insight gained by the authorities. In addition, a range of possible strategies are obtained, and not a single one which raises new questions on which one has to be eventually adopted. In our opinion it is more adequate to have a final decision over a limited time-horizon, say five years. In this way the strategy can be periodically revisited if necessary to better match the objectives.

6. A didactic example

To illustrate the approach we now present a small simulation example for reducing the CO_2-emissions in the residential sector (Kunsch et al., 1999).

The assumptions are the following:

- The time horizon is 60 months, thus five years;
- There are three abatement technologies ($K = 3$): rational use of energy ("rue"), High Efficiency of heating systems ("High Efficiency"), and use of wind turbines to produce locally electricity ("wind");
- Two experts ($n = 2$) with credibility factors ($0.5; 0.7$) draw MC-curves for all $k = 1, 2, 3$. Five anchor points ($L = 5$) are calculated from these curves and used for the set of five rules per technology and expert. The MC-curves $n = 1, 2$; $K = 1, 2, 3$ are shown in Figure 6.5;
- A total annual budget is imposed;
- Initial conditions with no abatement are defined.

Note from Figure 6.5 that the opinions of two experts are quite different, also with respect to the initial conditions, which indicates today-limited experience of these technologies. In particular, the marginal costs

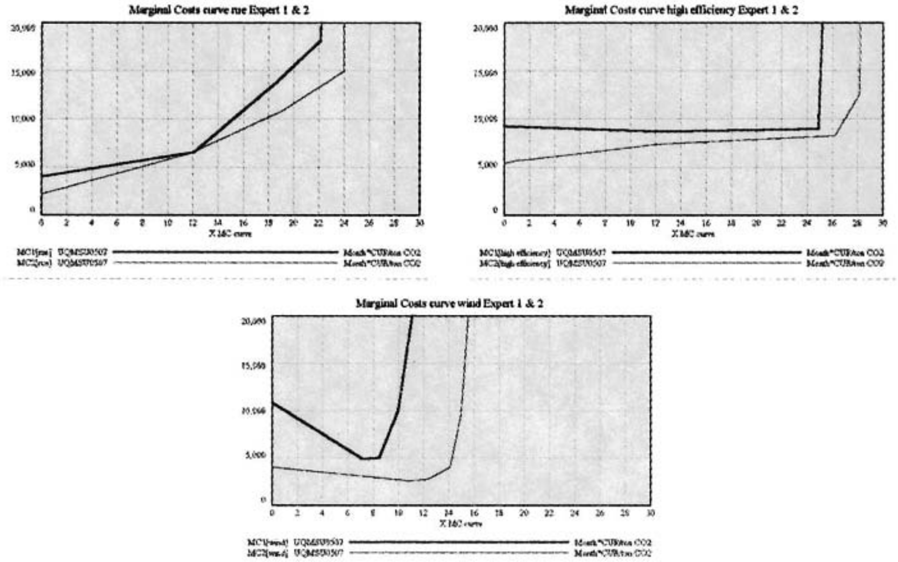


Figure 6.5. The MC-curves of the two experts for the three technologies left: "rue'; right: "high efficiency," lower: "wind."

of wind energy are a matter of controversy, about their initial value, and the way they will develop. This assumption of initially diverging opinions may not be very realistic, but it supports our demonstration on the ability to combine very different opinions. In particular the first expert, who is also the less credible one, has the more pessimistic opinion on how much wind energy will cost today and how much future potential is available.

For each technology, at each time step, a fuzzy-reasoning process takes place with those data, like shown in the methodological Section 5 (Figure 6.4). This first model was static. For our purpose it can easily be made dynamic: in each time value, the computed values of the variables from the previous time step are used for forward computing in the following time steps. We used for this time simulation the system dynamics code VENSIM® DSS32 (2000) for reasons of convenience, although it is not directly be taken advantage of feedback's dynamics. This code is easy to use, it has an easy-to-understand graphical interface, and it permits to work with vectors (subscripts), which is useful for large n, K, and L-values (other simulation tools could be used, e.g., SIMULINK®, which can be easily combined with the mentioned Fuzzy Toolbox of MATLAB®, but such development may require more programming skills).

We make no reference to real data for this simulation. For a more realistic model, the assumptions on the number of experts and technologies can be changed as wished. Also the assumption on constant credibility factors is easy to relax. VENSIM® has the capability of performing sensitivity analyses using random drawings from given probability distributions of model parameters.

Figure 6.6 shows the influence diagram, which is used to illustrate the modelling simplicity, though one must be aware that subscripts are hidden behind several variables. The equations of this model are available from the authors on request.

Important components of the model can be recognised:

- In the upper right corner comes the fuzzy-logic reasoning starting from five anchor values for the CO_2-levels, and combining the two opinions of the experts into one fuzzy price, given the two inputs: CO_2-levels for each technology and expert (scenario) credibility factors (compare with Figure 6.4). The abatement price is calculated by defuzzification in the middle part of the diagram;
- In the upper left corner the inverse first derivatives of the marginal costs is calculated for each active MC-curve; the auxiliary binary variable $B_1 = 1$ indicates an active technology at current time. The share of each technology is calculated according to eq. (6.11),

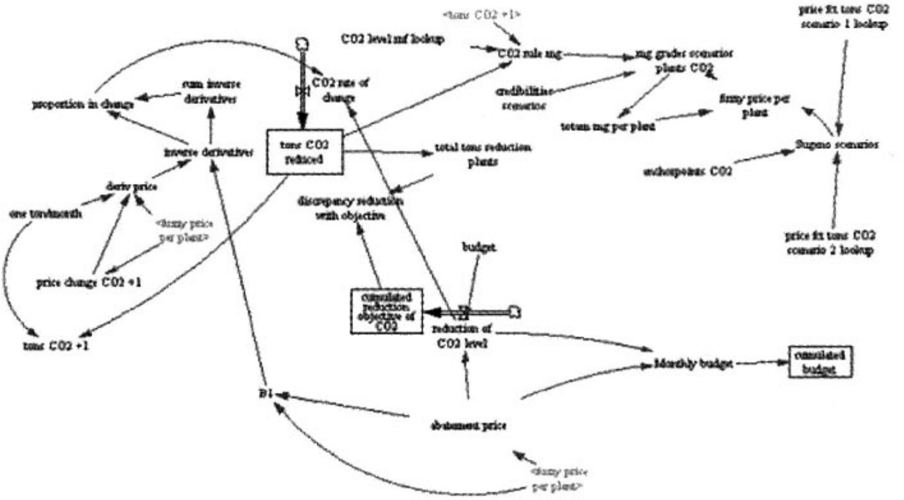


Figure 6.6. The influence diagram of the didactic example is commented in the main text.

giving the "CO_2 rate of change." The abatement per technology is accumulating in the stock indicated "tons CO_2 reduced."

- The desired reduction of the CO_2-level is calculated in the middle of the diagram from the constraint on yearly budget and the abatement price, according to eq. (6.13).

To illustrate the results, we first consider the calculation for the most credible expert alone, considering his credibility factor $C_2 = 0.7$. Note that though this sole expert is consulted in this case, this does not prevent from using his credibility factor smaller than 1 in the computing process (this is a basic difference with a weighing technique in which weights are summing up to one).

Figure 6.7 shows the three marginal curves MC_2 of this expert, while Figure 6.8 shows the CO_2-reduction evolution for all three technologies.

These results can be deduced by visual inspection from the three MC-curves (see Figure 6.3 and the attached explanations for comparison). Figure 6.9 shows the corresponding fuzzy prices per plant, from which the abatement price of Figure 6.10 can be deduced by taking the minimum value according to eq. (6.4).

We then analyse the combined case with 2 experts. Figures 6.11 and 6.12 give respectively the abatement price (equal to the permit price), and the total abatement of the three technologies. A comparison is made between the three cases: opinion of expert 1 alone ($C_1 = 0.5$); opinions of the two experts ($C_1 = 0.5, C_2 = 0.7$) combined with fuzzy

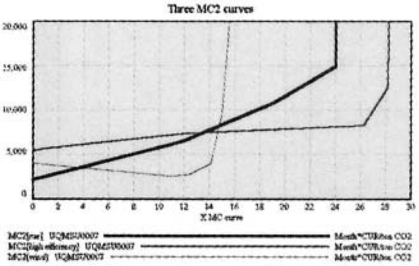


Figure 6.7. MC-curves for expert 2

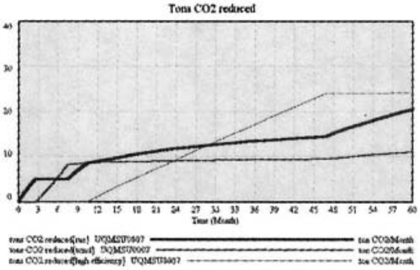


Figure 6.8. CO_2 reductions for expert 2

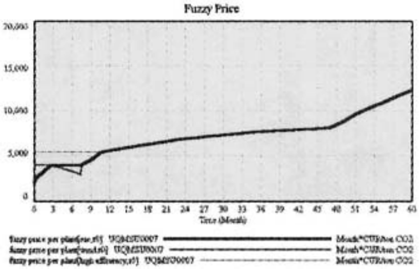


Figure 6.9. Fuzzy price for expert 2

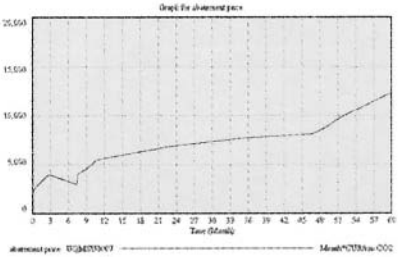


Figure 6.10. Abatement price for expert 2

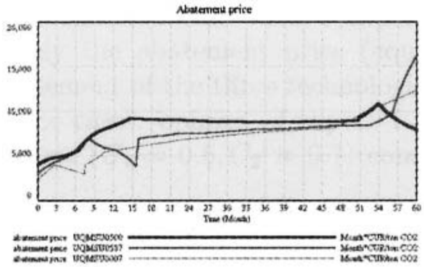


Figure 6.11. The abatement price equal to the permit price for three cases: upper curve, expert 1 alone ($C_1 = 0.5$); middle curve two experts ($C_1 = 0.5$, $C_2 = 0.7$); lower curve expert 2 alone ($C_2 = 0.7$)

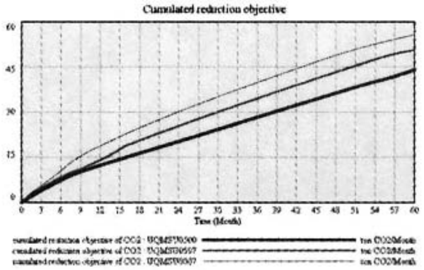


Figure 6.12. The total CO_2 abatement compatible with the budget for three cases: lower curve, expert 1 alone ($C_1 = 0.5$); middle curve two experts ($C_1 = 0.5$, $C_2 = 0.7$); upper curve expert 2 alone ($C_2 = 0.7$)

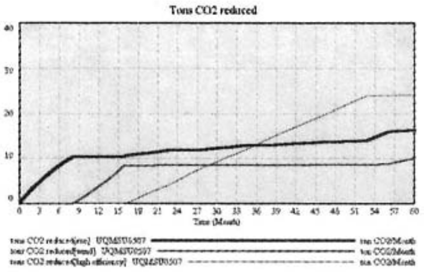


Figure 6.13. The CO_2-emission reduction per technology

reasoning; opinion of expert 2 alone ($C_2 = 0.7$). Figure 6.13 finally shows the detailed abatement per technology for the combined opinions of the two experts.

The comparison in Figures 6.11 and 6.12 with results coming from individual experts shows that the fuzzy treatment goes beyond simple weighed-sum rules for combining opinions. In addition partial opinions are distorted along the time-axis because of the dynamic abatement changes along the MC-curves. Remember also that a less credible partial opinion will count less in the global solution thanks to fuzzy-operators actions on the input side of rules (see eq. (6.21)).

7. Conclusions

Most pollution-control models are static and deterministic. In the present chapter we have presented a dynamic model aggregating an arbitrary number of opinions regarding possible evolution paths of the costs of abatement technologies. A didactic example relative to a CO_2-permit market has been presented in details.

The central driver of this model is based on fuzzy-reasoning rather than on probabilistic risk approaches of marginal abatement costs. We feel that in technically complex frameworks, like pollution control, it proves to be extremely difficult, if not impossible, to use time series from the past to extrapolate development in a rather distant future. Many past data, especially in the field of technology development are quite useless for forecasts. It is why the authors think that it is important to use the concept of "possibility," central to fuzzy reasoning, rather than the concept of "probability," central to the Bayesian approach of subjective probabilities. Imprecise statements like "small," "large," etc., are indeed better captured here by membership functions than by probability values.

Note that fuzzy logic can serve whenever there is ambiguity and imprecision with respect to numerical data to be used in any simulation model. In Kunsch and Fortemps (2002) one of the authors has shown an example of a two-stage fuzzy inference system (FIS). The "maturity level" of a technology is used as input to the first FIS: it provides as the final output of rules the membership function of the possible technology cost range. Because the maturity level is itself a fuzzy concept, a second FIS is developed where it appears in turn as the output. The future R&D budget needed for the further development of the technology is used as input to this second FIS. As in the present paper expert opinions with different credibility factors are used to assess the R&D budget.

In the present model on pollution abatement with permit schemes, we think that additional development is possible, upstream of the FIS we have presented. The idea is to better evaluate important input variables or parameters which we assumed so far to be given, like:

- The credibility of expert, which should indeed result from a previous analysis, one basic input to the FIS which needs further validation;
- The yearly budgets which serve as an input for determining the pace of development of abatement technologies.

As a last remark, we think that a model used for planning purposes in uncertain futures, and not amenable to probabilistic treatment, must rely on a regular updating of data (see, e.g., Brans et al., 2001). It is why it is recommended to consider a rather short rolling horizon, five years being a reasonable assumption.

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Chapter 7

MERGE: AN INTEGRATED ASSESSMENT MODEL FOR GLOBAL CLIMATE CHANGE

Alan S. Manne
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Abstract MERGE is a model for estimating the regional and global effects of greenhouse gas reductions. It quantifies alternative ways of thinking about climate change. The model contains submodels governing:

- the domestic and international economy;
- energy-related emissions of greenhouse gases;
- non-energy emissions of GHGs;
- global climate change - market and non-market damages.

1. Introduction

MERGE is a *Model for Estimating the Regional and Global Effects* of greenhouse gas reductions. It quantifies alternative ways of thinking about climate change. The model is sufficiently flexible to explore alternative views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting. It contains submodels governing:

- the domestic and international economy
- energy-related emissions of greenhouse gases
- non-energy emissions of ghg's
- global climate change — market and non-market damages.

Each region's domestic economy is viewed as a Ramsey – Solow model of optimal long-term economic growth. Intertemporal choices are strongly influenced by the choice of a "utility" discount rate.

Price-responsiveness is introduced through a top-down production function. Output depends upon the inputs of capital, labor and energy. Energy-related emissions are projected through a bottom-up perspective. Separate technologies are defined for each source of electric and nonelectric energy. Fuel demands are estimated through "process analysis."

Each period's emissions are translated into global concentrations and in turn to the impacts on mean global indicators such as temperature change. MERGE may be operated in a "cost-effective" mode — supposing that international negotiations lead to a time path of emissions that satisfies a constraint on concentrations or on temperature change. The model may also be operated in a "benefit-cost" mode — choosing a time path of emissions that maximizes the discounted utility of consumption, after making allowance for the disutility of abrupt climate change.

Individual geopolitical regions are defined. Abatement choices are distinguished by "where" (in which region?), "when" (in which time period?) and "what" (which greenhouse gas to abate?). There may be tradeoffs between equity and efficiency in these choices.

For a model of this size and complexity (currently, 20,000 constraints), there are several possible choices of nonlinear programming algorithms. We began with an informal decomposition procedure, but soon shifted to sequential joint maximization and iterative revision of Negishi weights. Our first solver was MINOS. We then coupled this with Benders decomposition. We are currently solving these problems with CONOPT3. For a computer listing and a bibliography, see our website: http://www.stanford.edu/group/MERGE

2. Market and non-market damages

If the model is operated in a benefit-cost mode, one must somehow quantify the benefits of slowing down the rate of climate change. Typically, these benefits are described in terms of the damages avoided. When Nordhaus (1991) made his first efforts at quantification, the benefits were expressed in terms of avoiding crop losses, forestry damage, shoreline erosion, etc. For each of these sectors, it was possible to assign market values to the losses. There are prices for crops, timber and real estate. Later, it was discovered that some changes (e.g., CO_2 fertilization) could even lead to modest gains in some of these areas. There is an emerging consensus that market damages are not the principal reason to be concerned over climate change.

The more worrisome issue is the type of damage for which there are no market values. The "non-market damages" include human health, species losses and catastrophic risks such as the shut-down of the thermohaline circulation in the Atlantic ocean. Here we must rely on imagination and introspection. We can be sure of only one thing. High-income regions are far more willing to pay to avoid this type of global loss than those with low incomes. Bangladesh has more reason to be concerned about typhoons than about Arctic ice flows.

In MERGE, we have allowed for both market and non-market damages, but have focused our attention on the latter. Our focal point is a 2.5° temperature rise — the "climate sensitivity" associated with a doubling of carbon concentrations over pre-industrial levels. For market damages, we have tried to summarize the literature by supposing that a 2.5° temperature rise would lead to GDP losses of 0.25% in the high-income nations, and to losses of 0.50% in the low-income nations. At higher or lower temperature levels than 2.5°, we have made the convenient assumption that market losses would be proportional to the change in mean global temperature from its level in 2000.

For non-market damages, MERGE is based on the conjecture that expected losses would increase quadratically with the temperature rise. That is, there are no discernible losses at the temperature level of 2000, but the losses from possible catastrophes could increase radically if we go much higher. Admittedly, the parameters of this loss function are highly speculative. With different numerical values, different abatement policies will be optimal.

This helps to explain why there is no current international consensus on climate policy.

3. The domestic economy

Within each region, intertemporal consumption and savings choices are governed by an optimal growth model. There is forward-looking behavior. Current and future prices and quantities are determined simultaneously. For a simple numerical example of this type of macro model, see the GAMS documentation for library model Ramsey.63.

The time paths of savings, investment and consumption are strongly influenced by the choice of a "utility" discount rate. This in turn may be governed by a prescriptive or a descriptive viewpoint. In the first case, one adopts a planner's perspective on how things *ought* to be managed. In the second, one adopts a utility discount rate that is intended to *describe* a market-oriented economy. For a review of different perspectives on discounting, see Portney and Weyant (1999).

Outside the energy sector, output is aggregated into a single good, the numéraire. Consumption is just one of the claimants upon total economic output, $Y_{\mathrm{rg,pp}}$. In each region rg and projection period pp, some of the output must be allocated to investment, $I_{\mathrm{rg,pp}}$. In turn, this is used to build up the capital stock. Other output is employed to pay for energy costs, $\mathrm{EC}_{\mathrm{rg,pp}}$. Some output is required to compensate for market damages, $\mathrm{MD}_{\mathrm{rg,pp}}$. And some output is allocated to net exports of the numéraire, $\mathrm{NTX}_{\mathrm{rg,pp,nmr}}$. The allocation equation is expressed as follows:

$$Y_{\mathrm{rg,pp}} = C_{\mathrm{rg,pp}} + I_{\mathrm{rg,pp}} + \mathrm{EC}_{\mathrm{rg,pp}} + \mathrm{MD}_{\mathrm{rg,pp}} + \mathrm{NTX}_{\mathrm{rg,pp,nmr}}.$$

Gross output is defined so that there is a low elasticity of price response in the short run, but a much higher response over the longer term. This is a "putty-clay" substitution process. That is, new output is responsive to current and expected future prices, but the economy is locked in to the technology choices made in earlier years. With ten-year time intervals and 40% depreciation over a decade, we have:

$$Y_{\mathrm{rg,pp}} = \mathrm{YN}_{\mathrm{rg,pp}} + .6Y_{\mathrm{rg,pp-1}}.$$

In turn, new output is based on an economy-wide nested CES (constant elasticity of substitution) production function. To allow for "putty-clay," the inputs to this production function are expressed as new capital, new labor, new electric and new nonelectric energy, respectively $\mathrm{KN}_{\mathrm{rg,pp}}$, $\mathrm{LN}_{\mathrm{rg,pp}}$, $\mathrm{EN}_{rg,pp}$ and $\mathrm{NN}_{\mathrm{rg,pp}}$. Each of these inputs is governed by transition equations similar to those that have just been written for gross output.

The production function is calibrated so as to allow for three types of substitution: (1) capital-labor substitution, (2) interfuel substitution between electric and nonelectric energy, and (3) substitution between capital-labor and energy. The parameters are also adusted so as to allow for autonomous improvements in the productivity of labor and of energy. New output is written as the following function of the new inputs:

$$\begin{aligned}\mathrm{YN}_{\mathrm{rg,pp}} \leq \Big(&\mathrm{aconst}_{\mathrm{pp,rg}}\mathrm{KN}_{\mathrm{rg,pp}}^{\rho_{\mathrm{rg}}\mathrm{kpvs}_{\mathrm{rg}}}\mathrm{LN}_{\mathrm{pp,rg}}^{\rho_{\mathrm{rg}}(1-\mathrm{kpvs}_{\mathrm{rg}})}\\ &+ \mathrm{bconst}_{pp,rg}\mathrm{EN}_{rg,pp}^{\rho_{\mathrm{rg}}\mathrm{elvs}_{rg}}\mathrm{NN}_{rg,pp}^{\rho_{\mathrm{rg}}(1-\mathrm{elvs}_{\mathrm{rg}})}\Big)^{1/\rho_{\mathrm{rg}}}\end{aligned}$$

4. The international economy

International trade is expressed in terms of a limited number of tradeable goods. These are handled through the Heckscher – Ohlin paradigm (internationally uniform goods), rather than the Armington specification (region-specific heterogenous goods). Specifically, we assume that each of the regions is capable of producing the numéraire good. This is identical in all regions, and may be either exported or imported. This is a crucial simplification. It means that heterogenous categories outside the energy sector (e.g., foodgrains, medical services, haircuts and computers) are all aggregated into a single item called "U.S. dollars of 2000 purchasing power." This is the type of simplification that is usually adopted in partial equilibrium models. Clearly, this would be inappropriate if we were dealing with short-term balance-of-payments issues for individual countries. Hopefully, it does not create a serious bias for the analysis of long-term issues such as climate change.

We assume that each of the regions may produce oil and gas (subject to resource exhaustion constraints), and that these commodities are tradeable between regions. In some versions of the model, we also allow for trade in eis (an aggregate representing *e*nergy-*i*ntensive *s*ectors such as steel and cement). And in other versions, we allow for trade in crt (carbon emission rights).

Generically, the tradeables are described by the index set, trd. The decision variables $\mathrm{NTX}_{\mathrm{pp,rg,trd}}$ may be positive (to denote exports) or negative (to denote imports). For each tradeable trd and each projection period pp, there is a balance-of-trade constraint specifying that — at a global level — net exports from all regions must be balanced with net imports:

$$\sum_{\mathrm{rg}} \mathrm{NTX}_{\mathrm{pp,rg,trd}} = 0.$$

Associated with each of these trade balance equations, there is a price. In a planning model, these would be described as "efficiency prices." MERGE, however, is a market-oriented model. We therefore refer to these as projections of market prices. There is enormous uncertainty with respect to these prices, and no careful user of the model should take them too literally.

Because the objective function of MERGE is stated in terms of discounted utility, each of the prices is also stated in terms of discounted utility. To improve intelligibility for the general user, we report these prices in terms of their ratio to the value of the numéraire good during each projection period. However, at the point in the computational cycle where we adjust the Negishi weights so as to ensure an intertemporal balance-of-payments constraint for each region, these are once again defined as present-value prices. For more on the Negishi adjustment process, see Rutherford (1999).

5. Energy-related emissions of greenhouse gases

Within the energy sector, virtually all emissions of greenhouse gases consist of carbon dioxide. For purposes of this presentation, we shall skip over the small amount of methane produced by coal mining and by natural gas extraction and transportation.

MERGE contains carbon emission coefficients for both current and prospective future technologies. These define how much carbon dioxide is produced whenever we burn coal, oil and gas in the generation of electric and non-electric energy. Carbon dioxide is *not* released when we generate electricity through nuclear, hydroelectric, geothermal, wind and solar photovoltaics. Another carbon-free option is combustion, followed by capture and sequestration. Currently, aside from traditional non-commercial biomass, there are virtually no economical carbon-free sources of non-electric energy. It is expensive to produce hydrogen directly through the electrolysis of water, and it is also expensive to produce ethanol from crops such as grain and sugar.

Over the long term, it is possible that we could consume all of the fossil fuels contained in the earth's crust, and that this would set an upper bound on the emissions of carbon dioxide. Unfortunately — from the perspective of global climate change — this does not provide a very tight bound on greenhouse emissions. In MERGE, we are currently using the regional and global estimates of oil and gas resources that appear in U.S. Geological Survey (2000). "Undiscovered" resources are based upon the USGS F5 (optimistic) scenario for resources to be discovered during the thirty-year period 1995 – 2025. For our reference case, global oil and gas production reach their peak about 2050. There are, however, enormous quantities of coal resources. Coal-fired electricity generation and coal-based synthetic fuels could lead to a quadrupling of carbon dioxide emissions over the 21st century. Coal may provide energy security for a few countries (China, India, Russia and the USA), but it could lead to an unprecedented rise in global carbon concentrations.

6. Non-energy emissions of ghg's — afforestation sinks of CO_2

For non-energy emissions, MERGE is based on the estimates provided by Energy Modeling Forum Study 21. The EMF estimated baseline projections from 2000 through 2020. Our baseline was in turn derived by linear extrapolation through 2100.

For the abatement of non-energy emissions, MERGE is also based on EMF 21. EMF provided estimates of the abatement potential for each gas in each of 11 cost categories in 2010. We incorporated these abatement cost curves directly within the model and extrapolated them after 2010, following the baseline. We also built in the possibility of technical advances in abatement over time.

Our estimates of carbon sinks are based on the global results reported by two of the models participating in EMF 21: GCOMAP and GTM. For details on these models, see, respectively, Sathaye et al. (2003) and Sohngen and Mendelsohn (2003). Each of these is a dynamic partial equilibrium model of the timber industry. That is, both of these models take the efficiency price of carbon as an input datum. Each allows for the carbon uptake in the timber growth cycle, and each gives an estimate of timber supplies, demands and prices in individual markets.

GTM and GCOMAP were run under six standardized scenarios with respect to the global efficiency price of carbon. For each of these scenarios, the models then reported the year-by-year net absorption of carbon through afforestation sinks. In turn, the two models were each coupled to MERGE by taking a convex combination of the six time-phased scenarios — and allowing for the possibility of a delay in initiating them.

7. Global climate change — cost-effectiveness analysis

Ideally, one would project global climate change by estimating precipitation, snowfall and other meteorological events. As a practical matter, the mean global temperature is the most readily available indicator. To estimate the temperature increase from 2000, we followed the IPCC (2001, p. 358) suggestions, and took the increase in radiative forcing as proportional to the differences in:

- logarithm of carbon dioxide concentrations
- square root of methane and nitrous oxide concentrations
- short- and long-lived F-gas concentrations.

Radiative forcing determines the potential for temperature increase — after *time* has elapsed for the system to come into equilibrium. In order to translate radiative forcing into the actual temperature increase, we must allow for time lags in response. Both the biosphere and the ocean systems introduce inertia into the system — an average lag of about 25 years. This is modeled through a series of linear difference equations.

The end result is an estimate of the mean global temperature increase that is associated with a reference case (business-as-usual) and with alternative abatement strategies. Figure 7.1 is based on the MERGE estimates submitted to EMF 21. It shows a reference case leading to radiative forcing of 8.4 watts per square meter by 2150 — and a temperature increase of 4.5°C from 2000. It also shows two control cases — both

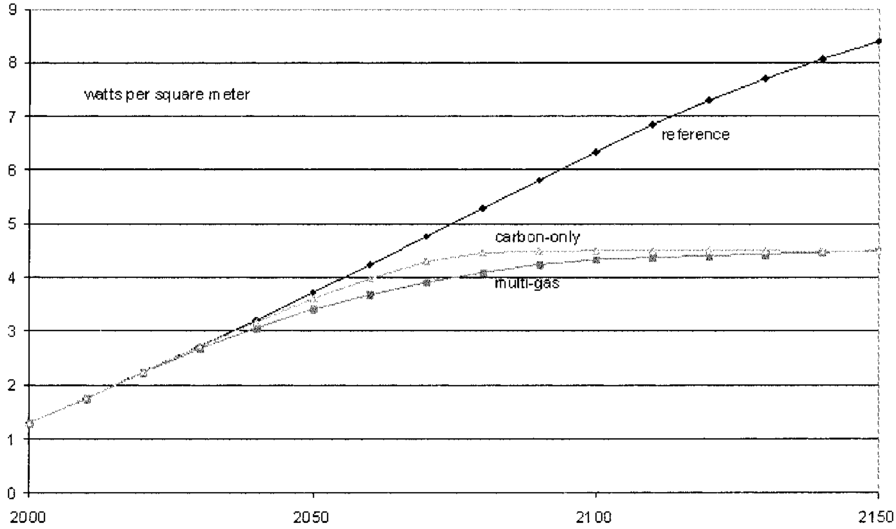

Figure 7.1. Radiative forcing — from 1750

of them providing for a limit of 4.5 watts per square meter. One is based on a carbon-only abatement strategy. The other is based on a multi-gas approach. Associated with each of these strategies, there is an efficiency price path — an optimal tax on the emissions of carbon and the other greenhouse gases. See Figure 7.2.

8. Benefit-cost analysis

Figures 7.1 and 7.2 are based upon the cost-effectiveness paradigm. That is, what is the least-cost way to satisfy a given limit? For EMF, the limit is stated in terms of radiative forcing or in terms of the mean global temperature increase. But one can also pose this as a benefit-cost problem — reaching agreement on an international control system that leads to the best temperature limit. This is a more ambitious goal. It requires us to define the disutility that is associated with varying amounts of market and nonmarket damages.

In order to quantify these tradeoffs, we have assumed a specific form for the "economic loss factor," $ELF_{rg,pp}$. For non-market damages, MERGE is based on the conjecture that expected losses would increase quadratically with the temperature rise. Figure 7.3 shows the admittedly speculative estimates that are currently used in MERGE. Different numerical values are employed — depending upon the per capita income of the region at each point in time. These loss functions are based on two

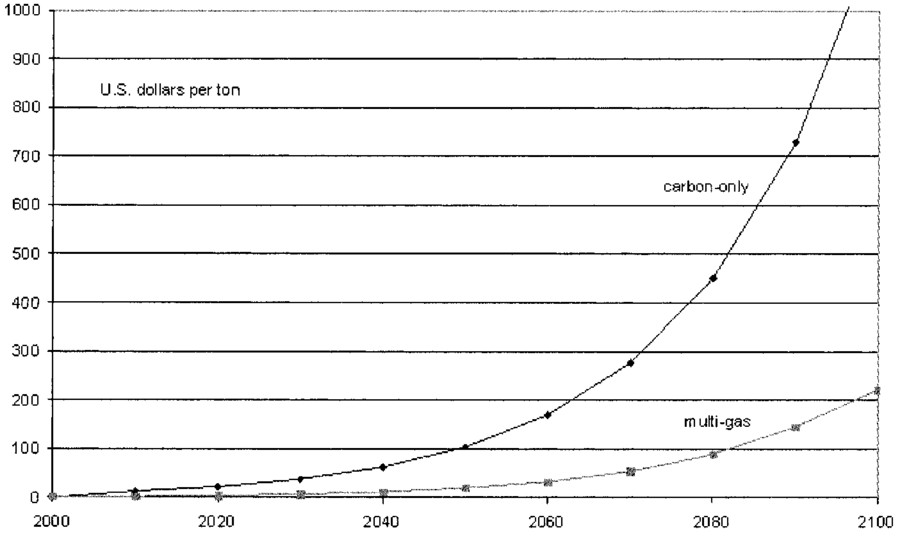

Figure 7.2. Efficiency price of carbon

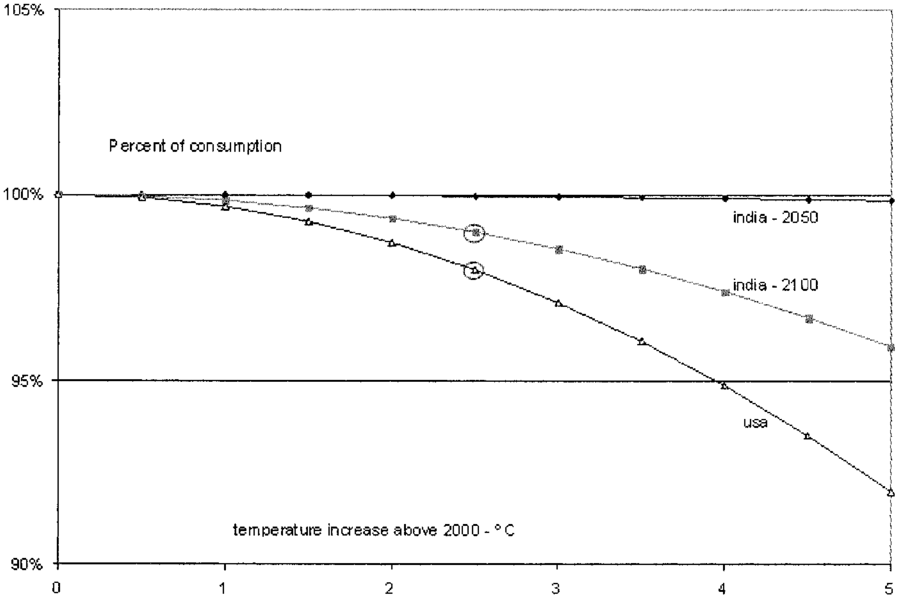

Figure 7.3. Economic loss factor — nonmarket damages

parameters that define willingness-to-pay to avoid a temperature rise: *catt* and *hsx*.

To avoid a 2.5° temperature rise, Annex B (high-income countries) might be willing to give up 2% of their GDP. (Why 2%? This is the total GDP component that is currently devoted by the U.S. to all forms of environmental controls — on solids, liquids and gases.) On Figure 7.3, this is expressed as an "economic loss factor" of 98% associated with a temperature rise of 2.5°. (The loss factor at 2.5° is circled on the two lower curves.) This factor represents the fraction of consumption that remains available for conventional uses by households and by government. For high-income countries, the loss is quadratic in terms of the temperature rise. That is, in those countries, the hockey-stick parameter hsx = 1. In general, the loss factor is written as:

$$\mathrm{ELF}(x) = [1 - (x/\mathrm{catt})^2]^{\mathrm{hsx}}$$

where x is a variable that measures the temperature rise above its level in 2000, and catt is a catastrophic temperature parameter chosen so that the entire regional product is wiped out at this level. In order for ELF(2.5°) = .98 in high-income nations, the catt parameter must be 17.7°C. This is a direct implication of the quadratic function.

What about low-income countries such as India? In those countries, the hsx exponent lies considerably below unity. It is chosen so that at a per capita income of $25 thousand, a region would be willing to spend 1% of its GDP to avoid a global temperature rise of 2.5°. (See loss factor circled on the middle curve.) At $50 thousand or above, India might be willing to pay 2%. And at $5 thousand or below, it would be willing to pay virtually nothing. To see how these parameters work out, consider the three functions shown on Figure 7.3. At all points of time, the U.S. per capita GDP is so high that ELF is virtually the identical quadratic function of the temperature rise. Now look at India. By 2100, India's per capita GDP has climbed to $25 thousand, and ELF is 99% at a temperature rise of 2.5°. In 2050, India's per capita GDP is still less than $4 thousands, and that is why its ELF remains virtually unity at that point — regardless of the temperature change.

Caveat: Admittedly, both catt and hsx are highly speculative parameters. With different numerical values, one can obtain alternative estimates of the willingness-to-pay to avoid non-market damages. One example will be given below. Although the numerical values are questionable, the general principle seems plausible. All nations might be willing to pay something to avoid climate change, but poor nations cannot afford to pay a great deal in the near future. Their more immediate priorities will be overcoming domestic poverty and disease.

We are now ready to incorporate the *ELF* functions into the maximand of MERGE. The maximand is the Negishi-weighted discounted utility (the logarithm) of consumption — adjusted for non-market damages:

$$\text{Maximand} = \sum_{\text{rg}} \text{nwt}_{\text{rg}} \sum_{\text{pp}} \text{udf}_{\text{pp,rg}} \cdot \log(\text{ELF}_{\text{rg,pp}} C_{\text{rg,pp}})$$

where:

nwt_{rg} = Negishi weight assigned to region rg – determined iteratively so that each region will satisfy an intertemporal foreign trade constraint

$\text{udf}_{\text{pp,rg}}$ = utility discount factor assigned to region rg in projection period *pp*

$\text{ELF}_{\text{rg,pp}}$ = economic loss factor assigned to region rg in projection period pp

$C_{\text{rg,pp}}$ = conventional measure of consumption (excluding non-market damages) assigned to region rg in projection period pp.

How much difference does it make if we employ different values for the parameters underlying $\text{ELF}_{\text{rg,pp}}$, the economic loss functions? Suppose, for example, that we were to double the economic loss associated with a 2.5° temperature increase. Instead of a 2% economic loss for high-income nations, *all* nations are willing to give up 4% of their economic output to avoid this temperature increase. For benefit-cost analysis, our standard case will be labeled PTO, a Pareto-efficient scenario. The alternative case will be labeled "high WTP," a high willingness to pay to avoid climate change.

The implications are shown in Figures 7.4 – 7.6. With a high WTP, the optimal temperature increase is slightly lower, carbon abatement begins earlier, and there is a higher early efficiency price of carbon. Note, however, that these changes are gradual. Even with a high WTP, the temperature and the carbon emissions path depart only gradually from the reference case in which no damage values are assigned to temperature change. By the way, with a high WTP, the optimal radiative forcing turns out to be roughly the same as the EMF 21 cost-effectiveness parameter of 4.5 watts/square meter.

9. Algorithmic issues: LBD and ATL

This note will conclude with our experience related to two algorithmic issues. One is LBD (learn-by-doing), and the other is ATL (act-then-learn). LBD arises from the observation that the accumulation of experience generally leads to a reduction in costs. This is often described in terms of a "learning curve" — a nonlinear relation implying, for example, that a doubling of cumulative experience will result in a 20% cost re-

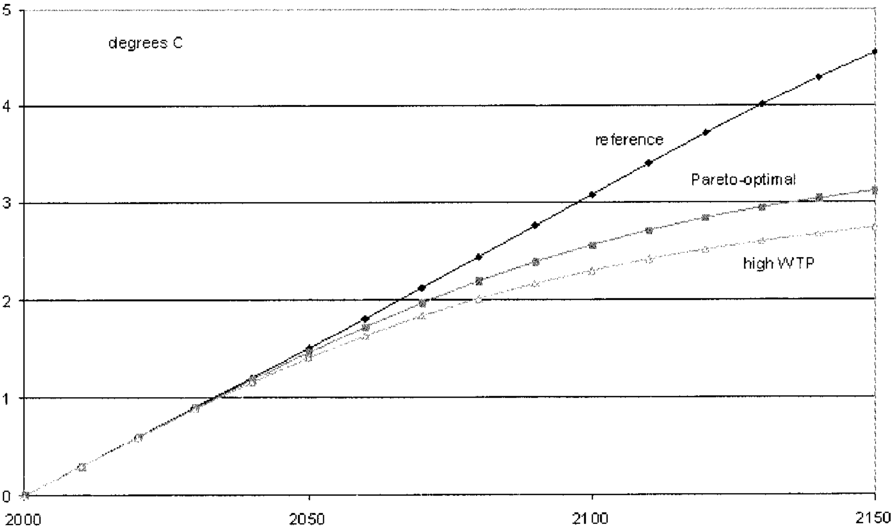

Figure 7.4. Temperature increase from 2000

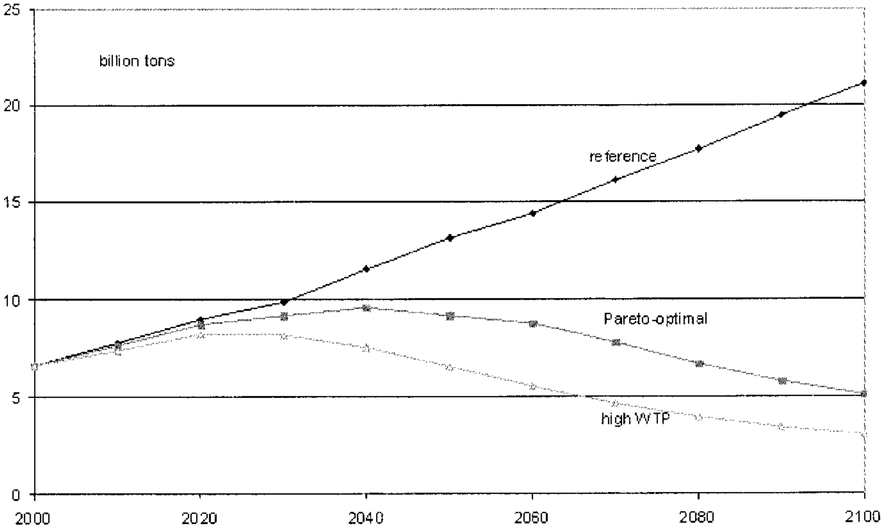

Figure 7.5. Total carbon emissions

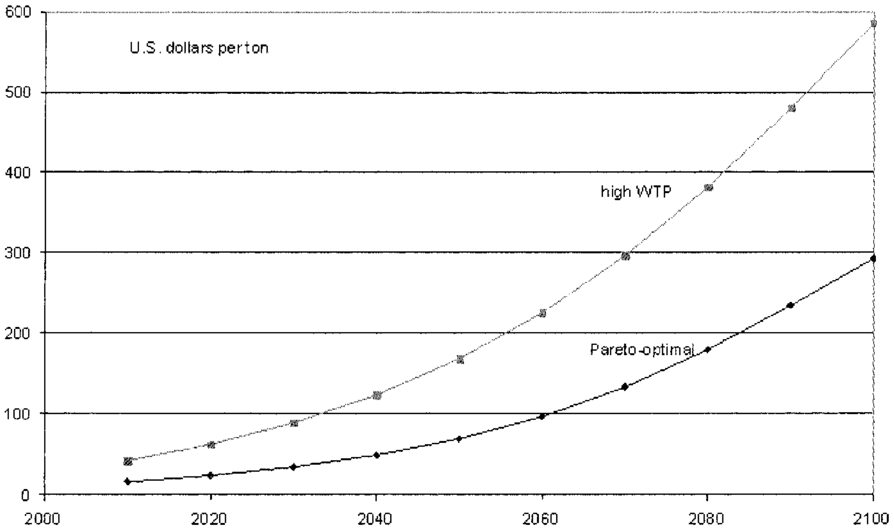

Figure 7.6. Efficienty price of carbon

duction. This form of learning curve may be incorporated directly into a nonlinear programming model such as MERGE, but there is a difficulty. A learning curve leads to non-convexities. In turn, this means that a local optimum will not necessarily be a global optimum. For an energy-related example of a local optimum, see Manne and Barreto (2004).

Fortunately, in the case of small models, a global optimum can be recognized and guaranteed through an algorithm such as BARON. See Sahinidis (2000). MERGE, however, is too large, however, for anything like the current version of BARON. Instead we have resorted to a heuristic based on terminal conditions. Typically, this consists of specifying that at the end of the planning horizon (e.g., 2150), the cumulative experience with an LBD technology must be at least, say, 10 times the initial experience. Typically, this is a nonbinding constraint, and it does not affect the solution. If an LBD technology is attractive, it will usually end up with cumulative experience that is hundreds or thousands of times larger than the initial value.

But what if this terminal constraint is binding? With small models, our experience is that a binding constraint implies that the LBD technology is unattractive, and that it is not optimal to introduce it into the global mix. In any case, the terminal conditions heuristic has enabled us to explore the proposition that LBD leads to a radically different strategy for greenhouse gas abatement. This is usually described as a rapid initial jump in the deployment of high-cost, carbon-free technologies. It is true that rapid deployment can lead to cost reductions via learning, but our experience is that the optimal abatement policy is one that involves only a gradual shift rather than an abrupt departure from the business-as-usual path. See Manne and Richels (2002). Energy installations are capital-intensive, and there is too much inertia in the system for it to be attractive to abandon long-lived equipment such as oil refineries and coal-fired power plants.

What has been our experience with ATL (act, then learn) models for decisions under uncertainty? No matter what one's views on the need for greenhouse gas abatement, ATL is an attractive paradigm. It is not a controversial proposition to say that today's decisions must be made under uncertainty, and that some of these uncertainties will be resolved with the passage of time. The principal difficulties are: (1) reaching agreement on the subjective probabilities of the uncertainties and (2) defining a date by which these uncertainties are likely to be resolved. There is also the fact that ATL enormously expands the difficulty of numerical solution.

With 20,000 constraints, there is no difficulty in solving MERGE with current nonlinear programming algorithms. But if we were to deal with uncertainty by considering just ten uncertain states of the world, this could lead to models with nearly 200,000 linear and nonlinear constraints. Eventually, it should be possible to solve problems of this size, but — with the current state of the art of computing — this doesn't seem immediately feasible. Instead, we have considered two rather different approaches, and plan to report on them at a future date. One is a straightforward algorithmic development — Benders decomposition. We have already had experience with this type of decomposition on smaller scale problems, see Chang (1997). For future work, it will be essential to develop software that facilitates modifications in the Benders problem statements.

An alternative to this type of large-scale computing is to aggregate regions and technologies — not necessarily at the beginning of the planning horizon, but to do this after the lapse of several time periods. With market-oriented discount rates, we have observed that the near-term solution is dominated by one's assumptions about the near term. Long-term abatement considerations are important, but — because of discounting — the exact form of these assumptions is not critical for near-term decisions.

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Chapter 8

A MIXED INTEGER MULTIPLE OBJECTIVE LINEAR PROGRAMMING MODEL FOR CAPACITY EXPANSION IN AN AUTONOMOUS POWER GENERATION SYSTEM

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Abstract The paper presents the application of Mixed Integer Multiple Objective Linear Programming (MIMOLP) in the power generation expansion problem of Crete for the period 2005 – 2020. The developed 3-period MIMOLP model includes two conflicting objectives (cost and CO_2 emissions minimization) continuous and integer variables and a number of operational and logical constraints. The model is solved with the Multi-Criteria Branch and Bound (MCBB) method that provides all the efficient solutions for MIMOLP problems. A sensitivity analysis is performed in order to handle the uncertainty related to the future electricity demand in the island. Interesting conclusions are drawn from the trade offs between the two objective functions. They reveal that contrary to a fixed perception, the integration of the CO_2 reduction objective can lead to solutions that are not only environmentally benign but also economically attractive in view of the potential exchange of emission permits in the framework of the emission trading mechanism.

1. Introduction

Energy planning objectives and modeling approaches have known radical changes in early eighties. The concern for the depletion of conventional energy resources and the need to cope with the ongoing environmental degradation, implied an apparent conflict to the economic grounds of the so far planning principles and advocated for the use of Multiple Criteria Decision Making (MCDM) methods. In a recent survey paper the evolution of MCDM approaches in energy planning has been analytically investigated, in proportion with the emerging problems faced by utilities and other stakeholders (Diakoulaki et al., 2004).

In the mathematical programming context, the multiple criteria concept appears firstly in the form of Goal Programming and Multiple Objective Linear Programming (MOLP). Among the first applications of these models in energy planning are those of Cohon, 1978; Zionts and Deshpande, 1981; Kavrakoglu and Kiziltan, 1983; Schulz and Stephest 1984; Quaddus and Goh, 1985; Teghem and Kunsch, 1985. MOLP models continue to be increasingly used in order to effectively incorporate environmental and social considerations in energy decisions. (see, e.g., Chattopadhyay, 1995; Clímaco et al., 1995; Martins et al., 1996; Mavrotas et al., 1999; Hobbs and Meier 2000; Linares and Romero, 2000; Linares and Romero 2002; Antunes and Martins 2003; Oliveira and Antunes, 2003; Antunes et al., 2004). The objective functions generally considered include the minimization of the total expansion cost (or production cost) in the planning horizon, the minimization of pollutant emissions (CO_2, SO_2, NO_x), the maximization of the reliability/safety of the supply system, the minimization of the external dependence of the country or the minimization of a risk/damage indicator.

However, MOLP models are not able to accurately represent discrete phenomena which are often encountered in energy planning. Power dispatching, facility siting, power expansion are typical examples of such type of problems where some of the decision variables should be represented by integer and/or binary (0-1) variables.

In the particular case of the power generation expansion planning problem the aim is to identify the new capacity to be installed throughout a planning period and the output to be produced by each unit. The former refers to the system's structure as defined by the primary energy source, the energy conversion technology and the capacity of the new entrants, while the latter to the system's overall operational characteristics. A realistic modeling requires that structural characteristics are represented by integer (or binary) decision variables while the design and operational ones by continuous decision variables. This kind of problem is usually tackled by means of a Mixed Integer MOLP (MIMOLP) model.

The present paper is using the Multicriteria Branch and Bound (MCBB) method (Mavrotas and Diakoulaki, 1998). Following the usual discretization of MOLP models (see, e.g., Steuer, 1989), the MCBB method belongs to the generation methods that produce all the efficient points (supported and unsupported) in MIMOLP problems. If the size of the multi-objective problem is in manageable limits (up to a few hundreds of variables and constraints), generating approaches are usually more advantageous than interactive ones. In the last case the Decision Maker (DM) is provided by a sample of efficient solutions for driving the searching process. Instead, generating approaches illustrate the whole context of the decision situation and thus, reinforce the DM's confidence to the final decision. Besides, in real decision situations the frequent interaction with the DM, which is assumed by interactive approaches, is not always easy to achieve.

The case study presented in this paper refers to the Greek island of Crete. Crete is the fifth bigger island in the Mediterranean Sea and has an autonomous power generation system, due to its long distance from the Greek mainland. The existing system relies mainly on oil burning thermal power plants and must serve a rapidly increasing demand with high peaks related mostly to the island's tourist profile. The main challenges for the system diversification and its compliance to environmental obligations arise from the further exploitation of the island's rich wind potential and the possibility to use liquefied natural gas (LNG) in combined cycle units. Besides cost minimization, the planning procedure should incorporate the objective of minimizing CO_2 emissions reflecting the need to comply with the commitments of the Kyoto Protocol and the opportunity to exploit the flexibility offered by the forthcoming emission trading mechanism.

The rest of the paper is organized as follows: The methodological issues of the proposed method are described in the next section. The case study is presented in section three while the details of the model formulation are described in the fourth section. The results are discussed in section five and finally the basic concluding remarks are given in the last section.

2. Methodological approach

The Multi-Criteria Branch and Bound (MCBB) method used in this paper relies on a branch and bound approach that is appropriate to handle optimization problems with combinatorial features. The conventional branch and bound algorithm, which is widely used to solve mixed integer and mixed 0-1 linear programming problems, is properly modified in order to handle multiple objectives and to provide the whole set of efficient solutions. The MCBB algorithm was introduced in 1998 (Mavrotas and Diakoulaki 1998) and applications can be found in Mavrotas et al (1999; 2003).

The decision course in MIMOLP problems is usually a two-stage procedure. Particular attention is paid to the efficient combinations, e.g., the combinations of integer variables that generate efficient solutions.

One efficient combination may provide several efficient solutions which differ only in the continuous variables. The efficient combinations convey abundant information to the DM, since they usually represent the structure of the examined system while the associated efficient solutions determine the system's operational characteristics.

According to the MCBB method the combinatorial tree is traversed as in the single objective case using a depth first search. The procedure is modified in order to take account of the vector (instead of scalar) characteristics of the multiple objective problem. At each intermediate node the optimum of each objective function is calculated and the vector of the ideal point is formed. The final nodes represent the efficient combinations where all 0-1 variables are assigned to either 0 or 1. At each final node the set of the corresponding efficient extreme points is generated and stored in the list L_{ef}. This list is dynamic and is updated whenever a final node is visited: the new efficient points are compared with those already stored in L_{ef}, in order to discard the dominated ones. In accordance with the incumbent solution of the single objective case the list L_{ef} is called incumbent list. The points which remain in the incumbent list after the completion of the combinatorial tree's searching constitute the efficient solutions of the multiple objective problem.

A branch of the combinatorial tree can be terminated prematurely if the problem of the corresponding node becomes infeasible or if the fathoming condition is fulfilled. The fathoming condition states that if the ideal point of a node is dominated by any other point stored in the incumbent list then the search is useless and the branch is terminated.

In comparison with the single objective case the multiple objective procedure is much more computational intensive (see, e.g., Rasmussen, 1986; Ulungu and Teghem, 1994). It performs multiple optimizations in each intermediate node, the fathoming condition is harder to meet due to the vector (instead of scalar) comparisons, the updating of the incumbent list is much more complicated than the updating of the incumbent solution and finally, the generation of the efficient solutions in the final nodes (the most time consuming part of the algorithm) is a rather complicated procedure. The module for the generation of efficient points in the final nodes is based on the Multicriteria Simplex Method for vector maximization (Zeleny, 1982). It generates the relative efficient points using the Evans – Steuer criterion for the identification of the efficient movements in the Simplex algorithm (Steuer, 1989). The successive optimizations needed for the calculation of the ideal point at each node are performed using the "warm start" technique (starting from the last optimal base). The interested reader may refer to Mavrotas and Diakoulaki (1998; 2002) for a more detailed description of the method.

Table 8.1. Forecasted power demand for the island of Crete

	Peak Power (MW)	Energy (GWh)
2006	458	2524
2010	557	3068
2015	678	3733
2020	786	4327

Since its first edition, new elements have been added to the MCBB method in order to increase its speed, reliability and capacity to handle larger problems. These new elements refer to computational and methodological improvements such as the use of Revised Simplex with bounded Variables and Dual Simplex (see, e.g., Murtagh, 1981), the detection of convex dominated solutions in the L_{ef}, and the systematic exploitation of the notion of efficient combination in the decision making process.

3. The case study

The case study under consideration refers to the expansion of the electricity system in the Greek island of Crete for the period 2006 – 2020. Crete is the fifth biggest island in the Mediterranean Sea with about 600,000 inhabitants and an area of 8,331 km^2. It is characterized by high rates of GDP growth, along with high tourism development that doubles its population during the summer. The implication of this growth pattern is a rapid increase in power demand (mean annual rate of increase 7% in the period 1980-2000). For the examined period the forecasted mean annual rate of increase in electricity demand is 5% for the period 2006-2010, 4% for the period 2011-2015 and 3% for the period 2016-2020. The respective forecasts for the peak power and the total electricity demand are shown in Table 8.1.

The power generation facilities in the island include steam turbines and internal combustion engines burning Heavy Fuel Oil (HFO), gas turbines and a combined cycle unit burning diesel oil. The capacity of existing wind parks is already amounting at 70 MW, which is still a relatively small portion of the rich wind potential of the island. Most conventional power plants are using old technologies and are characterized by low efficiencies. During the next 10 years half of them will complete more than 35 years in operation and have to be replaced. Moreover, the fast increase of power demand requires a gradual expansion of the existing system in order to safely meet the electricity demand for the next 15 years. The characteristics of the existent units are shown in Table 8.2.

The names in parentheses represent the code name of each unit in the developed model. Candidate units for the future are steam turbines, gas turbines, combined cycle units burning diesel or natural gas and wind parks. New Internal Combustion Engines are excluded as being considered as unsuitable technology. The economically exploitable wind potential of the island is estimated at more than 500 MW. The natural gas for the combined cycle units is provided by tankers in liquefied form (LNG). Their investment cost includes the cost of a terminal (pressurized tank) which has to be constructed in order to store the imported amounts of LNG that are going to be consumed in the power plants. The feasibility study for this project is already completed but the construction is not decided yet. The characteristics of the candidate units are shown in Table 8.3.

Table 8.2. Basic characteristics of the existent power generation units

Unit	Net Capacity (MW)	Fuel	Commitment year	Availability factor
Steam turbine 1 (ST1)	30	HFO	1971	0.8
Steam turbine 2 (ST2)	25	HFO	1977	0.8
Steam turbine 3 (ST3)	50	HFO	1982	0.8
Gas turbine 1 (GT1)	32	Diesel	1974	0.75
Gas turbine 2 (GT2)	73	Diesel	2003	0.75
Gas turbine 3 (GT2)	60	Diesel	1980	0.75
Internal Comb. Eng. (ICE1)	50	HFO	1989	0.75
Internal Comb. Eng. (ICE2)	100	HFO	2003	0.75
Combined Cycle (CCD)	132	Diesel	1994	0.85
Wind parks (W)	70		1998–2000	0.3

Table 8.3. Basic characteristics of the candidate units

Unit	Net Capacity (MW)	Fuel	Availability factor
Steam turbine (NST)	50–200	HFO	0.82
Gas turbine (NGT)	20–80	Diesel	0.78
Combined Cycle (NCCD)	50–200	Diesel	0.87
Combined Cycle (NCCNG)	50–200	Natural gas	0.87
Wind parks (NW)	0–500		0.3

4. Model formulation

The MIMOLP model developed for the power generation expansion of the island of Crete, is driven by two objective functions, one economic (minimization of total expansion cost) and one environmental (minimization of CO_2 emissions). The aim of the multi-objective formulation is to find those combinations of power generation units which result in efficient solutions, taking into account both, economic and environmental concerns. The second objective function represents the increasing awareness for CO_2 emissions, especially under the prism of the flexible mechanisms imposed by the Kyoto Protocol. With the emission trading mechanism the reduction of CO_2 emissions' offers a greater flexibility to the electricity market players, among which Public Power Corporation is the largest one, owning at present all conventional power units. Therefore, before establishing an action plan for the island's electricity system, it is advisable to examine a broad range of solutions.

4.1 Demand modeling and load duration curves

The planning horizon (2006 – 2020) is decomposed into three equal periods, namely 2006 – 2010, 2011 – 2015 and 2016 – 2020. The electricity demand to be satisfied for each period is described by the corresponding Load Duration Curve (LDC) showing the number of hours per period in which the power demand (in megawatts) exceeds a given value. The LDC for each period is calculated by aggregating the corresponding annual LDCs as defined in Table 8.1. The area under the LDC represents electricity production in megawatt-hours. In order to comply with the linear requirements of the solution procedure the LDC is approximated by a piecewise-constant function (histogram) (Stoll, 1989; Climaco et al., 1995; Martins et al., 1996). A four-bar histogram is used for representing the LDC for Crete, assuming that its shape remains constant for the three periods. Figure 8.1 shows the curve for the period 2011 – 2015.

Each bar defines an orthogonal sub-section of the total area. Bar 1 refers to the base load, bar 4 to the peak load, while the other two intermediate bars represent middle load demand. The obtained results for the power demand after the linearization of the LDC for the three periods are shown in Table 8.4.

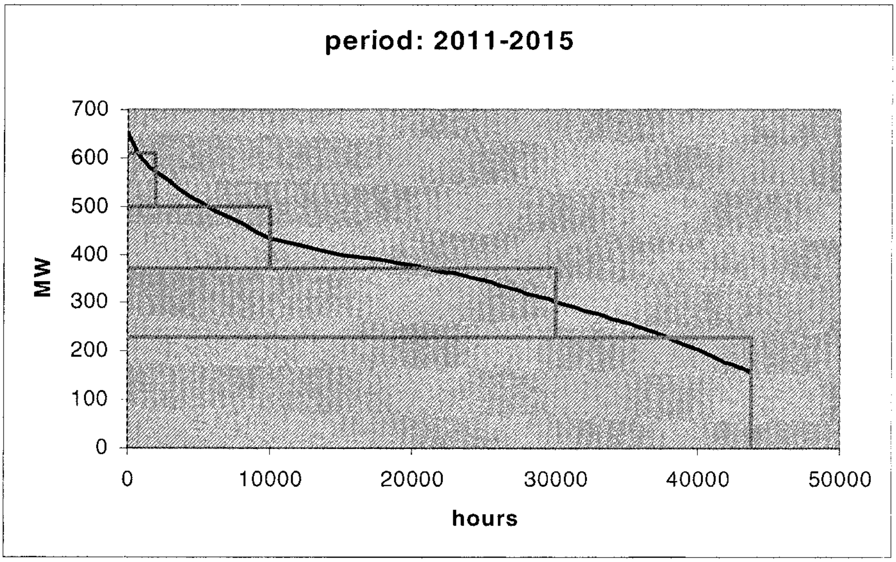

Figure 8.1. Linearization of the LDC for period 2011-2015

Table 8.4. Power demand data for the planning horizon

	Time (hours)	Power (MW) Period 1 (2006–10)	Period 2 (2011–15)	Period 3 (2016–20)
Subsection 1 (base load)	43800	180	230	280
Subsection 2 (middle-base load)	30000	300	370	450
Subsection 3 (middle-peak load)	10000	400	500	600
Subsection 4 (peak load)	2000	530	650	780

4.2 Decision variables, objective functions and constraints

For the description of the decision variables, objective functions and constraints we must first define the basic nomenclature. The following parameters and decision variables are used in the model:

n: the number of subsections in the LDC ($n = 4$)

s: the number of periods in the planning horizon ($s = 3$)

m: the number of types of existent units ($m = 5$, i.e., ST, GT, ICE, CCD, W)

nm: the number of types of candidate units (nm = 5, i.e., NST, NGT, NCCD, NCCNG, NW)

X_{ijk}: continuous decision variable expressing the output in MW of the ith type unit, in the jth period, in the kth sub-section of the LDC.

CAP_{ij}: continuous variable expressing the capacity in MW of the new unit of ith type that is installed in period j

B_{ij}: binary decision variable expressing the decision to construct an ith type unit in order to be operational in period j

B_{Tj}: binary decision variable expressing the decision to construct the LNG terminal in order to be operational in period j ($j = 2, 3$).

The continuous decision variables refer to the design (capacities) and the operational characteristics (output) of the system. The binary variables refer to the structural characteristics of the system. With the use of binary variables a more realistic modeling of the decision situation is obtained reflecting the minimum capacity requirements for the new units and the logical conditions to be taken into account. In the case of wind parks, the introduction of new capacity is modeled with continuous variables because of the small size of individual wind turbines.

Objective functions. The first objective function concerns the minimization of the discounted electricity production cost (expressed in thousand Euro of 2000). It includes fuel cost, operational & maintenance (O&M) cost as well as the investment cost for the new units discounted with 5%. In the case of the gas-fired combined-cycle unit it also includes the investment cost for the required LNG terminal discounted also with 5%. The fuel cost is assumed to increase with an annual escalation factor of 2%. The mathematical relationship for the first objective function is as follows:

$$\min \sum_{i=1}^{m+\mathrm{nm}} \sum_{j=1}^{s} \sum_{k=1}^{n} h_k \cdot v_{ijk} \cdot X_{ijk} + \sum_{i=1}^{\mathrm{nm}} \sum_{j=1}^{s} \mathrm{fc}_{ij} \cdot \mathrm{CAP}_{ij} + \sum_{j=2}^{s} \mathrm{fc}_{Tj} \cdot B_{Tj} \quad (8.1)$$

where h_k is the number of hours in subsection k, v_{ijk} the variable cost (fuel cost and operational & maintenance cost) that characterizes the kth subsection of the jth period of the ith unit, fc_{ij} is the discounted investment cost per MW of the ith type of unit in period j (only for new units), fc_{Tj} is the discounted investment cost for the LNG terminal. The variable cost (in 2000 prices) and the investment cost for the new units are shown in Table 8.5, while the investment cost for the LNG terminal is estimated at 135 million € (2000 prices).

The second objective function is the minimization of the CO_2 emissions produced by conventional power generation units during the plan-

Table 8.5. Variable and investment cost for the power units in Crete

	Variable cost (€/MWh)	Investment cost (€/kW)
Steam turbines	33	1570
Gas turbines	69	375
Internal combustion engines	30	–
Combined Cycle with diesel	57	775
Combined Cycle with natural gas	34	790
Wind parks	5	1330

ning horizon and is expressed as:

$$\min \sum_{i=1}^{m+\mathrm{nm}} \sum_{j=1}^{s} \sum_{k=1}^{n} \mathrm{ef}_i \cdot h_k \cdot X_{ijk} \tag{8.2}$$

where ef_i is the CO_2 emission factor in tCO_2/MWh of the ith type of unit, which is 0.74 for steam turbines, 1.08 for gas turbines, 0.65 for internal combustion engines, 0.53 for combined cycle with diesel and 0.4 for combined cycle with natural gas.

Constraints. The constraints of the MIMOLP model can be classified in the following basic categories:

Capacity constraints. The output of each type of power generation unit cannot exceed the total capacity of the existing or planned units of this type, multiplied by the corresponding availability factor. For the existent units the following relation holds:

$$\sum_{k=1}^{n} X_{ijk} \leq \mathrm{af}_i \times \mathrm{totalcapacity}_{ij}, \quad i = 1, \ldots, m, j = 1, \ldots, s \tag{8.3}$$

where af_i is the availability factor of the ith type of unit and $\mathrm{totalcapacity}_{ij}$ is the available capacity of the ith type of unit in the jth period (see Table 8.2). The availability factor (presented in Tables 8.2 and 8.3) is calculated by taking into account the forced outage rate and the scheduled maintenance of each unit according to the relation:

$$\mathrm{af}_i = \left(1 - \frac{\mathrm{mw}_i}{52}\right) \times (\mathrm{FOR}_i) \tag{8.4}$$

where mw_i is the number of the scheduled maintenance weeks and FOR_i is the forced outage rate expressed in terms of probability for the unit of type i. For the wind parks an average availability factor is calculated according to the frequency of winds with exploitable velocity during the year.

For the candidate units the corresponding relation is slightly modified to:

$$\sum_{k=1}^{n} X_{ijk} - \mathrm{af}_i \times \sum_{i \le j} \mathrm{CAP}_{ij} \le 0, \quad i = m+1, \ldots, m+\mathrm{nm},\ j = 1, \ldots, s \qquad (8.5)$$

where CAP_{ij} is the installed capacity of the ith type unit during period j. In order to increase the model's flexibility, the capacity of the new units is allowed to vary within specific limits as it is proposed by Liu and Sahinidis (1997). This flexibility is incorporated in the model with the following two constraints:

$$\mathrm{CAP}_{ij} - \mathrm{mincap}_i \times B_{ij} \ge 0 \quad \text{for } i = m+1, \ldots, m+\mathrm{nm},\ j = 1, \ldots, s \qquad (8.6)$$

$$\mathrm{CAP}_{ij} - \mathrm{maxcap}_i \times B_{ij} \le 0 \quad \text{for } i = m+1, \ldots, m+\mathrm{nm},\ j = 1, \ldots, s, \qquad (8.7)$$

where mincap_i and maxcap_i are the minimum and maximum allowable capacities as shown in Table 8.3 and B_{ij} is the binary variable that denotes the installation of a unit of type i in period j.

For the wind parks the additional economic potential is more than 500 MW. However, the upper bound for the installation of wind parks is regulated by the relative legislation stating that every year the total installed capacity of wind parks cannot exceed 33% of the peak power demand recorded in the previous year. Therefore the upper bound for the capacity of the new wind parks is appropriately adjusted according to the peak demand of the specific period, taking into account the already installed capacity of 70 MW.

Demand satisfaction. According to the present modeling approach the power demand is expressed by the corresponding subsections of the LDC. Therefore, for each sub-section the marginal power demand according to Figure 8.1 is considered. The corresponding relation is:

$$\sum_{i=1}^{m+\mathrm{nm}} X_{ijk} \ge \Delta p_{jk} \quad k = 1, \ldots, n\ j = 1, \ldots, s, \qquad (8.8)$$

where Δp_{jk} is the marginal power requirement as expressed by the subsection k of the jth period's. The values for Δp_{jk} are calculated from the linearized LDC using the formula $\Delta p_{jk} = p_{jk} - p_{jk-1}$ with $p_{j0} = 0$. For example, in the LDC of Figure 8.1 that represents the 2nd period's power demand (2011–2015) we have $\Delta p_{21} = 230 - 0 = 230$, $\Delta p_{22} = 370 - 230 = 140$, $\Delta p_{23} = 500 - 370 = 130$ and $\Delta p_{24} = 620 - 500 = 120$.

Reserve margin. The reserve margin is defined as the difference between the installed capacity and the required peak demand for a specific period. In the present case the reserve margin is set to 20% which means that the installed capacity for each period j must be 20% greater than the corresponding peak demand as expressed by the following relation:

$$\sum_{i=m+1}^{m+\mathrm{nm}} \mathrm{CAP}_{ij} + \sum_{i=1}^{m} \mathrm{totalcapacity}_{ij} \geq 1.2 p_{jn}, \quad j = 1, \ldots, s, \tag{8.9}$$

where the first term refers to the new units and the second term to the existent units.

Link between natural gas units and LNG terminal. The construction of the LNG terminal is a prerequisite for the construction of the natural gas fired combined cycle units. According to the feasibility study, these projects should be built close one to the other and the most appropriate location is the small island of Dia close to the northern coast of Crete. The final decision for the introduction of natural gas in the power generation system in Crete is still pending. Given this situation it is assumed that natural gas units will be operational no earlier than 2010 which means that they will be available for the second and third period of the planning horizon. Two binary variables, namely, B_{T2} and B_{T3} are introduced in the model to represent the decision to complete the LNG terminal before 2011 (the beginning of the second period) and before 2016 (the beginning of the third period) respectively. The logical constraints associated with the above conditions are the following:

$$B_{T2} \geq B_{\mathrm{NCCNG2}} \tag{8.10}$$

$$B_{T2} + B_{T3} \geq B_{\mathrm{NCCNG3}} \tag{8.11}$$

$$B_{T2} + B_{T3} \leq 1. \tag{8.12}$$

The first constraint implies that if the natural gas unit is operational in period 2 ($B_{\mathrm{NCCNG2}} = 1$), then the LNG terminal must also be present ($B_{T2} = 1$). The second constraint implies that if the natural gas unit is operational in the 3rd period then the LNG terminal must have been completed before the second or the third period. The third constraint declares that B_{T2} and B_{T3} are mutually exclusive alternatives (the terminal cannot be constructed two times).

Table 8.6. Participation of units in LDC subsections

	Base load	Base-middle load	Middle-peak load	Peak load
ST	X	X	X	
GT			X	X
ICE		X	X	
CC Diesel	X	X	X	X
CC Natural gas	X	X	X	X
Wind parks	X	X		

Constraints for mutually exclusive alternatives. The steam turbines and the combined cycle units (which both cover mainly the base and medium load) are considered to be mutually exclusive alternatives in the sense that the decision to build a steam turbine in period j prevents the decision to build also a combined cycle in the same period and vice versa. This is a reasonable assumption in order to avoid two different capital intensive investments in the same period. The condition is expressed as:

$$B_{\mathrm{NST1}} + B_{\mathrm{NCCD1}} \leq 1 \tag{8.13}$$

$$B_{\mathrm{NST}j} + B_{\mathrm{NCCD}j} + B_{\mathrm{NCCNG}j} \leq 1 \quad \text{for } j = 2, 3 \tag{8.14}$$

Further assumptions. The common practice implies that each type of unit is usually operating in a specific subsection of the LDC. For example it is irrational to use the gas turbines to serve base load or steam turbines to serve peak loads. Table 8.6 shows the association of each type of unit to the specified subsections of the LDC as implied by usual practice. With this reasonable assumption the number of the decision variables of the model is significantly reduced and the solution procedure is accelerated.

The resulting model comprises 107 decision variables of which 13 are binary, 75 constraints and two objective functions.

5. Results and discussion

Basic model

The above described MIMOLP model is solved with the MCBB algorithm in 20′ 36″ (in a Pentium III 800 Mhz) and 27 efficient extreme solutions were generated belonging to 9 efficient combinations. The efficient frontier illustrating the *trade-off* between the two objective functions is shown in Figure 8.2.

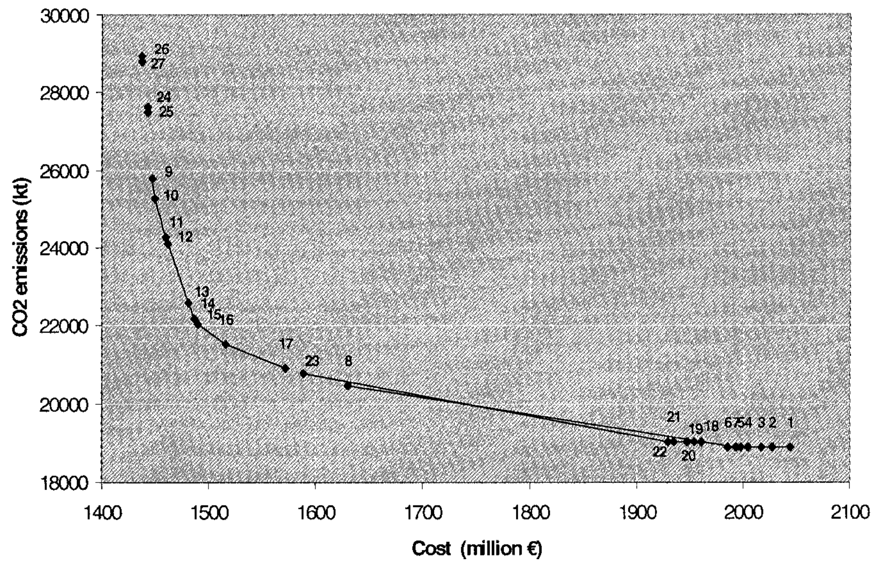

Figure 8.2. The tradeoff curve between CO_2 emissions and cost for 2006 – 20

The shape of the efficient frontier is typical for the trade-offs between economic and environmental objectives. Furthermore, it can be seen that a considerable reduction in CO_2 emissions can be achieved with relatively low costs (see the region comprising the efficient solutions 9 – 15 and 24 – 27). The solutions shown in the rest of the tradeoff curve are much less cost-effective in reducing CO_2 emissions. For the present case, in the upper part of the trade-off curve the cost of CO_2 emission reduction is about 8 – 10 €/tCO_2 as calculated from the relative slope, while in the lower part the cost of CO_2 emission reduction amounts at 200 €/tCO_2! This information, provided by the tradeoff curve, is very useful for establishing a cost-effective CO_2 abatement strategy. In addition, it can help the market players in an emission trading system towards right investment decisions. If for example in the emission trading market, the cost for an emissions permit is going to vary between 15 and 30 €/ton of CO_2, it is advisable to encourage actions leading to the implementation of the solutions in the "knee" of the curve (i.e., efficient solutions 14, 15 or even 16). In this way the tons of CO_2 saved do not only represent a considerable environmental benefit but also an economic profit attainable within the emission trading market.

The characteristic of the generated efficient solutions and the corresponding efficient combinations specifying the necessary investment plans are shown in Table 8.7. The first conclusion from Table 8.7 is that there are options that are not implemented in any of the efficient solutions (idle options). Specifically, the installation of a steam turbine in the first period and the diesel combined cycle units in periods 2 and 3 are not eligible for none of the 27 efficient solutions. On the other hand the wind parks are present in all the efficient solutions. The most economic structural pattern is the one implied by efficient combination 9, which assumes the installation of a steam turbine in period 2 and 3, a gas turbine in all three periods and also wind parks in the three periods. On the opposite side of the trade-off curve lies the most environmentally-benign structural pattern implied by efficient combination 1, and assuming the installation of gas turbines in periods 1 and 2, a diesel fired combined cycle unit in period 1, a natural gas fired combined cycle unit in periods 2 and 3 and wind parks in all three periods. As we can see from Table 8.7 the efficient combination 4 offers the greatest flexibility by generating the largest number of efficient solutions As shown also in Figure 8.2 these efficient solutions present significant differences in the generated CO_2 emissions. The efficient combination 4 assumes the installation of a gas turbine and wind parks in period 1 and natural gas fired combined cycle units with wind parks in periods 2 and 3.

The values of all the decision variables in all the efficient solutions as reported in the output file of the program provide valuable information to the DMs. Namely, besides the cost, the CO_2 emissions and the investment plan, detailed information is provided, regarding the output of each one of the operating units in each one of the subsections of the LDC. Thus, the operational plan assumed by each efficient solution for all three periods is analytically specified.

5.1 Sensitivity analysis

Given the extended planning period, the most uncertain parameter in the present model is the electricity demand. In order to increase the confidence on the model results, a sensitivity analysis with respect to the level of future electricity demand is performed by considering the four scenarios shown in Table 8.8. The escalation along the periods is attributed to the fact that the uncertainty increases as we are moving to longer term forecasts.

The first scenario derives 43 efficient solution and 17 efficient combinations in $56' \; 32''$, the second scenario 33 efficient solutions and 10 efficient combinations in $36' \; 19''$, the third scenario 25 efficient solutions and 9 efficient combinations in $10' \; 06''$ and finally the fourth scenario 22 efficient solutions and 9 efficient combinations in $5' \; 33''$. The solution

Table 8.7. The characteristics of the efficient solutions according to the investment program

efficient solution	cost (million €)	CO_2 (kt)	efficient combination	ST1	ST2	ST3	GT1	GT2	GT3	CCD1	CCD2	CCD3	CCNG2	CCNG3	W1	W2	W3
1	2044	18887	1	0	0	0	75	52	0	200	0	0	200	200	105	40	43
2	2027	18890	1	0	0	0	46	74	0	200	0	0	200	200	105	40	43
3	2017	18893	1	0	0	0	46	49	0	200	0	0	200	200	105	40	43
4	2005	18896	1	0	0	0	46	20	0	200	0	0	200	200	105	40	43
5	1998	18898	2	0	0	0	46	0	20	200	0	0	200	200	105	40	43
6	1985	18903	2	0	0	0	46	0	20	200	0	0	200	200	105	40	43
7	1993	18899	3	0	0	0	46	0	0	200	0	0	200	200	105	40	43
8	1630	20475	3	0	0	0	20	0	0	50	0	0	200	200	105	40	43
9	1447	25789	4	0	0	0	68	0	0	0	0	0	141	163	55	90	43
10	1449	25255	4	0	0	0	49	0	0	0	0	0	158	163	105	40	43
11	1460	24266	4	0	0	0	49	0	0	0	0	0	158	163	105	40	43
12	1461	24104	4	0	0	0	49	0	0	0	0	0	158	163	105	40	43
13	1481	22588	4	0	0	0	49	0	0	0	0	0	158	163	105	40	43
14	1487	22190	4	0	0	0	49	0	0	0	0	0	192	129	105	40	43
15	1490	22037	4	0	0	0	49	0	0	0	0	0	200	133	105	40	43
16	1515	21541	4	0	0	0	49	0	0	0	0	0	200	200	105	40	43
17	1571	20903	4	0	0	0	49	0	0	0	0	0	200	200	105	40	43
18	1961	19020	5	0	0	0	0	39	20	200	0	0	200	200	105	40	43
19	1954	19022	5	0	0	0	0	20	39	200	0	0	200	200	105	40	43
20	1947	19024	6	0	0	0	0	0	59	200	0	0	200	200	105	40	43
21	1936	19028	6	0	0	0	0	0	20	200	0	0	200	200	105	40	43
22	1930	19030	7	0	0	0	0	0	0	200	0	0	200	200	105	40	43
23	1588	20770	7	0	0	0	0	0	0	50	0	0	200	200	105	40	43
24	1443	27632	8	0	62	0	80	80	0	0	0	0	0	163	38	107	43
25	1443	27488	8	0	62	0	80	80	0	0	0	0	0	163	55	90	43
26	1437	28947	9	0	62	110	80	80	68	0	0	0	0	0	38	107	43
27	1437	28803	9	0	62	110	80	80	68	0	0	0	0	0	55	90	43

time drops because the former problems are more relaxed than the latter ones (less electricity demand must be satisfied) and therefore fewer nodes are infeasible in the branch and bound tree. The values of the objective functions in the efficient solutions are shown in the Cost-CO_2 emissions plane as the corresponding efficient frontiers.

It is evident that the relative position of the tradeoff curve is moving to the north-east of the diagram as the power demand grows since a higher demand implies a higher cost and more CO_2 emissions. It is noteworthy that the shape of the trade-off curves is similar for all the

Table 8.8. Electricity demand scenarios relative to the base scenario

	Scenario code	Changes in power demand relative to the base scenario		
		2006–10	2011–15	2016–20
Scenario 1	"low"	−10%	−15%	−20%
Scenario 2	"slightly lower"	−5%	−7.5%	−10%
Scenario 3	"slightly higher"	5%	7.5%	10%
Scenario 4	"high"	10%	15%	20%

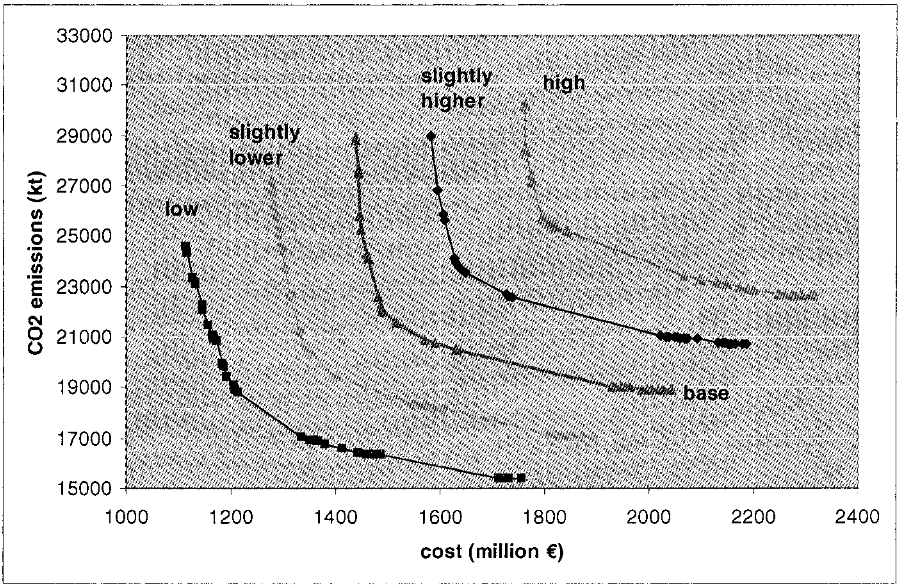

Figure 8.3. Trade-off curves for the five scenarios

scenarios meaning that the shape of the trade-off curve is not sensitive to the power demand. Namely, the cost of reducing the CO_2 emissions is low in the upper part of the curve and increases dramatically in the lower part.

According to the conclusions of Section 5.1 the most promising investment plans are those located on the "knee" of the tradeoff curves. In all the scenarios these investment plans have common characteristics. First of all, they almost fully exploit the allowable wind potential. They use natural gas fired combined cycle units in the second and third period and gas turbines in the first period. As demand is growing (high scenario) a combined cycle unit with diesel is also used in period 1.

6. Conclusions

Power generation expansion planning is still an interesting modeling challenge because of its complicated nature and the fact that relevant decisions have a long term character and must be carefully balanced. Despite the growing environmental concern and the increasing pressure from environmental commitments, in practice, the economic objective is still dominating the planning and decision process, with environmental considerations being either completely neglected or considered as rigid constraints. The mutli-objective paradigm increases the degrees of freedom for the multiple stakeholders of the electricity system who are not confined to the least cost "optimal" solution, but are offered with a deeper insight to the problem potential solutions and guided towards better quality decisions.

The incorporation of integer variables in the MOLP problems offers a more realistic modeling approach. The minimum capacity size of the new units, the logical conditions, the possible economies of scale in the investment cost cannot be modeled without the use of integer or binary variables.

The MCBB algorithm is proposing a general-purpose solution procedure, which provides all the efficient extreme solutions by at the same time spotlighting the corresponding efficient combinations in MOMILP problems. Although goal programming and interactive approaches dominate the field of the Multi-Objective Programming, the generation approaches have the great advantage of providing a thorough view on the whole solutions space. The rich information provided can be properly managed in order to firmly guide the decision process towards the most desired solution. Moreover, the continuous increase in computer power is expected to enhance the implementation area of generation methods and of the MCBB algorithm to larger problems.

In the specific case study considered in this paper, the proposed MI-MOLP approach offers appealing results leading to interesting conclusions. The incorporation of the CO_2 emissions as a second objective function besides cost minimization reveals a diversity of solutions that with the ordinary least cost optimization would remain undiscovered. The sharp change in the obtained trade-off curve points on a set of promising and environmentally cost-effective solutions. The cost-effectiveness of these "knee" solutions entails the additional advantage of potential future economic profits in view of the forthcoming emissions trading mechanism. This conclusion is further supported after the sensitivity analysis performed with respect to the level of power demand. Wind power units, natural gas fired combined cycle units, and gas turbines are found to be the main technologies for the environmentally cost-effective expansion of power generation system of Crete.

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Chapter 9

TRANSPORT AND CLIMATE POLICY MODELING THE TRANSPORT SECTOR: THE ROLE OF EXISTING FUEL TAXES IN CLIMATE POLICY

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Abstract Existing fuel taxes play a major role in determining the welfare effects of exempting the transportation sector from measures to control greenhouse gases. To study this phenomenon we modify the MIT Emissions Prediction and Policy Analysis (EPPA) model to disaggregate the household transportation sector. This improvement requires an extension of the GTAP data set that underlies the model. The revised and extended facility is then used to compare economic costs of cap-and-trade systems differentiated by sector, focusing on two regions: the USA where the fuel taxes are low, and Europe where the fuel taxes are high. We find that the interplay between carbon policies and pre-existing taxes leads to different results in these regions: in the USA exemption of transport from such a system would increase the welfare cost of achieving a national emissions target, while in Europe such exemptions will correct pre-existing distortions and reduce the cost.

1. Introduction

An explicit representation of transportation is important for quantitative analysis of energy and environmental policy. This sector is among the more rapidly growing energy users, and fuel inputs are often taxed at much higher rates in transportation than in other areas of the economy. Also, policies directed toward energy use and environmental control generally give special treatment to the transportation sector (particularly the automobile). For example, transportation has been treated differently from other sectors in the design of cap-and-trade systems. The European Union excludes the transportation sector from the 2005–07 trial period of its emission trading system (CEU, 2003), and the proposed US Climate Stewardship Act of 2003 (Paltsev et al., 2003) would impose an upstream system for emissions from transportation fuels and a downstream system for those from other sectors.

The goal of this paper is to study the welfare implications of a sector-specific cap-and-trade system that gives special treatment to industrial and household transportation. For analyzing climate policy many researchers use the GTAP dataset (Hertel, 1997), which incorporates detailed accounts of regional production and bilateral trade flows. Version 5 of this dataset (Dimaranan and McDougall, 2002) has three transportation sectors. However, household transportation expenditures on private automobiles are not represented explicitly in the data. The resulting aggregation of automobile fuel use with other transport fuels makes it impossible to study household transportation explicitly. To facilitate the needed analysis we have developed a method for augmenting the existing GTAP data to disaggregate household transportation (Paltsev et al., 2004a), and here we apply this new data facility within the MIT Emissions Predictions and Policy Analysis (EPPA) model to explore the effects of exempting the transportation sector from a carbon policy. In general, exemption of some sectors implies increased carbon tax rates for others and higher costs for an economy as a whole. However, a carbon policy may interact with existing taxes and economic distortions to produce counterintuitive effects. We compare two regions: the US, which has low fuel taxes, and Europe, where fuel taxes are high.

Our presentation of the data development and analysis is organized in the following way. In the next section we describe the modeling approach, and the sources of the household transportation data used to augment the existing GTAP structure. The modified household transportation sector, disaggregated into purchased and own-supplied transport, is described. Corresponding adjustments to other aspects of the household demand structure are also presented. Section 3 discusses methodological issues regarding capital accounting in the personal transport sector. Section 4 reports the key results of an analysis of the welfare effects of exclusion of industrial and household transport from a carbon policy. In Section 5 we draw some conclusions about the importance of model and data improvements needed to adequately assess climate policies, taking account of the full complexity of their introduction into pre-existing policy environments.

2. Disaggregating household transport

The GTAP5 dataset represents production and trade flows for 66 regions and 57 sectors of the world economy (Dimaranan and McDougall, 2002). Among those sectors are three transportation sectors: air transport (ATP), water transport (WTP), and other transport (OTP). The OTP sector includes land transport, transport via pipelines, supporting and auxiliary transport activities, and activities of travel agencies. Commercial transportation services purchased by the household from ATP, WTP, or OTP are already treated in the standard GTAP5 data, and this feature allows us to represent explicitly the substitution possibilities between own-supplied transportation and purchased transport services.

The missing component in GTAP is the transportation service produced by the household itself, i.e., that provided by private automobiles. Our strategy for modeling household transportation is to create a household production activity that combines goods purchased from industry with fuel inputs to produce an "own-supplied" transportation service that represents the use of personal automobiles. Transport-related purchases of the household are, of course, already included in consumer final demands. In some cases we can assume that final consumption from a GTAP sector is used exclusively in own-supplied transportation, but in other cases only a part of a sector's contribution is used in transportation. The data problem is to identify the appropriate sectors and to estimate the share of final consumption from these sectors that goes to own-supplied transportation. For energy and environmental modeling purposes, for example, a critical data need is to separate purchases of refined oil (gasoline and diesel fuel) used to fuel vehicles from those fuels used for home heating and other household purposes.

The revised data set is then applied in the EPPA model, which is a recursive-dynamic multi-regional general equilibrium model of the world economy (Babiker et al., 2001). Besides the GTAP data set, EPPA is built on additional data for greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) and urban gas emissions. The version of EPPA used here (EPPA4) has been updated in a number of ways from the model described in Babiker et al. (2001). Most of the updates are presented in Paltsev et al. (2003). For use in EPPA the GTAP dataset is aggregated into the 16 regions and 10 sectors shown in Table 9.1. The base year of the EPPA model is 1997. From 2000 onward it is solved recursively at 5-year intervals. Because of the focus on climate policy, the model further disaggregates the GTAP data for energy supply technologies and includes a number of "backstop" technologies — energy supply

Table 9.1. Countries, regions, and sectors in the EPPA model

Country or Region	Sectors
Annex B	**Non-Energy**
United States (USA)	Agriculture (AGRI)
Canada (CAN)	Services (SERV)
Japan (JPN)	Energy Intensive products (EINT)
European Union+[a] (EUR)	Other Industries products (OTHR)
Australia/New Zealand (ANZ)	Transportation (TRAN)
Former Soviet Union[b] (FSU)	**Energy**
Eastern Europe[c] (EET)	Coal (COAL)
Non-Annex B	Crude Oil (OIL)
India (IND)	Refined Oil (ROIL)
China (CHN)	Natural Gas (GAS)
Indonesia (IDZ)	Electric: Fossil (ELEC)
Higher Income East Asia[d] (ASI)	Electric: Hydro (HYDR)
Mexico (MEX)	Electric: Nuclear (NUCL)
Central and South America (LAM)	Electric: Solar and Wind (SOLW)
	Electric: Biomass (BIOM)
Middle East (MES)	Electric: Natural Gas Combined Cycle (NGCC)
Africa (AFR)	Electric: NGCC with Carbon Capture (NGCAP)
Rest of World[e] (ROW)	Electric: Integrated Gas Combined Cycle with Carbon Capture (IGCAP)
	Oil from Shale (SYNO)
	Synthetic Gas (SYNG)

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

[b] Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B) and Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan which are not. The total carbon-equivalent emissions of these excluded regions were about 20% of those of the FSU in 1995. At COP-7 Kazakhstan, which makes up 5–10% of the FSU, total joined Annex I and indicated its intention to assume an Annex B target.

[c] Hungary, Poland, Bulgaria, Czech Republic, Romania, Slovakia, Slovenia.

[d] South Korea, Malaysia, Phillipines, Singapore, Taiwan, Thailand

[e] All countries not included elsewhere.

technologies that were not in widespread use in 1997 but could take market share in the future under changed energy price or climate policy conditions. This additional disaggregation and technology specification does not have a substantial direct effect on the transportation modeling we develop here. The EPPA model's production and consumption sectors are represented by nested Constant Elasticity of Substitution (CES) production functions (or the Cobb-Douglas and Leontief special cases of the CES). Capital applied in the industry production sectors is vintaged, but the capital implicitly embodied in the household vehicle stock is not — a topic to which we return in Section 3. The model is written in GAMS-MPSGE. It has been used in a wide variety of policy applications (e.g., Jacoby et al., 1997; Jacoby and Sue Wing, 1999; Reilly et al., 1999; Bernard et al., 2003; Paltsev et al., 2003; Babiker et al. 2003).

2.1 Inter-industry transportation

Transport in the EPPA model is represented by two activities: an industry transportation sector (aggregating the modal splits in the base GTAP5 data) and a household transportation sector. Industry transportation (TRAN) supplies services (both passenger and freight) to other sectors of the economy and to households. The nesting structure of the industry transportation sector is depicted in Figure 9.1, which shows that its output is produced using energy, capital, labor, and intermediate inputs from different industries. The substitution elasticities for this sector, labeled as $s_1, \ldots, s_7$, are provided in Table 9.2. At the top of the nest, intermediate inputs and the energy-labor-capital bundle are modeled as a Leontief composite. Both domestic and imported intermediate goods are used in the production activities, with elasticities of substitution between domestic and imported bundles, s_2, and between imports from different regions, s_3. The energy-labor-capital bundle is composed of separate energy and value-added nests. Energy inputs are nested into electricity and non-electric inputs, and value added (labor and capital). The data for modeling this sector come directly from ATP, WTP, and OTP sectors of the GTAP dataset.

Table 9.2. Elasticity of substitution values for the industry transportation sector

Notation	Elasticity	Value
s_1	between Energy-Capital-Labor and Intermediate Goods	0
s_2	between Domestic and Imported Intermediates	3
s_3	between Imports from different regions	5
s_4	between Energy and Value-Added	0.5
s_5	between Electricity and Other Energy	0.5
s_6	between Capital and Labor	1
s_7	between Non-electric Energy inputs	1

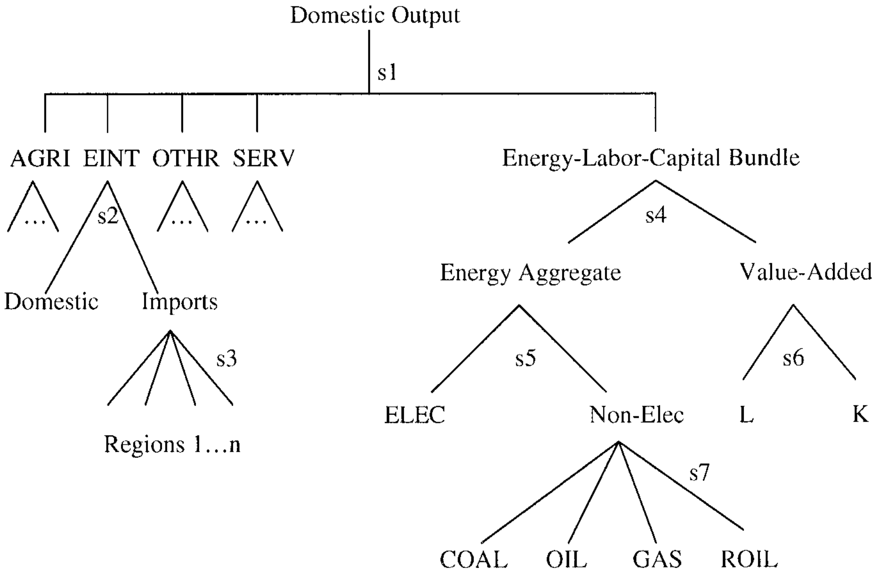

Figure 9.1. Structure of production for the industry transportation sector

2.2 Transportation in the household sector

Households consume both own-supplied (i.e., private cars) and purchased transport. Purchased transport (air travel, water travel, rail service, trucks, etc.) comes from the industry transportation sector described above. Own-supplied transportation services are provided using inputs from three sectors: Other Industries Products (purchases of vehicles), Services (maintenance, insurance, tires, oil change, etc.), and Refined Oil (fuel). In order to model the household transportation sector, we make use of the following identity:

$$\mathrm{OWNTRN}_r \equiv \mathrm{T\_ROIL}_r + \mathrm{AC}_r + \sum_i \mathrm{OC}_{ir}, \tag{9.1}$$

where OWNTRN_r stands for household expenditures on own-supplied transport in a region r, $\mathrm{T\_ROIL}_r$ is expenditures on refined oil used in household transportation (i.e., gasoline and diesel fuel), AC_r is vehicles, and OC_{ir} aggregates operating costs such as maintenance and repairs, insurance, financing costs, and parking — the last drawing on several sectors i. It is useful to define household expenditures on own-supplied transport as a share, ES_r , of total household expenditure,

$$\mathrm{OWNTRN}_r = \mathrm{ES}_r \times \mathrm{CONS}_r, \tag{9.2}$$

where CONS_r, total household expenditure in a region r, is available directly from the GTAP database. Often household expenditure data do not provide $\mathrm{T\_ROIL}_r$, but other energy surveys provide data on fuel expenditures, so that household expenditures on refined oil products for own-supplied transportation is usefully stated as a share, OS_r, of total household expenditure on all refined oil products, TOS_r:

$$\mathrm{T\_ROIL}_r = \mathrm{OS}_r \times \mathrm{TOS}_r, \tag{9.3}$$

with TOS_r available directly from the GTAP database.

In order to apply Equations (9.1) to (9.3) to the disaggregation of household transportation we need the data for AC_r, OC_r, ES_r, and OS_r. National surveys report that, for developed countries, household expenditures on own-supplied transport as a fraction of total household expenditures is approximately 0.1, and refined oil expenditures within household transportation is around 0.9 as a fraction of household expenditures on oil products — that is, most of the refined oil products used by households are for transportation. The share of own-supplied transportation expenditure (ES_r) can be estimated from household expenditure surveys. In particular, the OECD produces statistical handbooks on final consumption expenditure of households by purpose: (1) purchase of vehicles, (2) operation of vehicles (including oil), and (3) transport services (air tickets, railway tickets, etc.). Items (1) and (2) sum to OWNTRN_r. As shown in Table 9.3, these OECD data were used for the US, Canada, and Mexico. For the European Union we used data from household budget surveys by Member States (EUROSTAT, 1999). This database provides estimates for ES_r in Europe by summing three items: (1) car purchase, (2) motor fuels (including greases, etc.), and (3) other services (including repairs, insurance, etc.). The results are consistent with the OECD national accounts. For the other countries and regions, we use statistical handbooks and the United Nations national accounts that provide useful data on personal transport equipment (United Nations, 2002).

Since the OECD data do not disaggregate fuel expenditures from other operation expenditures we use estimates of OS_r to calculate $\mathrm{T\_ROIL}_r$ from Equation (9.3). Conveniently, as noted, the Eurostat database provides $\mathrm{T\_ROIL}_r$ estimates directly for the EU countries. The surveys that provide a disaggregation for oil consumption are from the Bureau of Economic Analysis for the USA, Statistics Canada (2002), and national statistical handbooks for some developing countries (e.g., China and India). When expenditure data are not available, physical data on oil consumption shares for private transportation and other residential uses combined with fuel tax and price data provide another approach. The

Table 9.3. Sources of data for own-transport expenditure (ES) and own-transport refined oil (OS) shares

Country or Region	ES	OS
United States	OECD (1997)	BEA (Moulton and Moylan, 2003)
Canada	OECD (1997)	Statistics Canada (2002)
Japan	Adjusted OECD (1997)	IEA data
EU	Eurostat (1999)	Eurostat (1999)
Australia/New Zealand	Adjusted UN (2002)	IEA data
Eastern Europe	Adjusted UN (2002)	IEA data
Former Soviet Union	World Bank data	IEA data
India	National statistical handbook	Ministry of Statistics & Programme Implementation (2001)
China	National statistical handbook	National Bureau of Statistics of China (2002)
Indonesia	Adjusted UN (2002)	IEA data
Dynamic Asia	Based on Korea (OECD, 1997)	IEA data
Mexico	OECD (1997)	IEA data
Central & South America	Based on Colombia (UN, 2002)	IEA data
Middle East	Based on Israel (UN, 2002)	IEA data
Africa	Based on South Africa, World bank data	IEA data

International Energy Agency (IEA/OECD) gives detailed energy balances in tons of oil equivalent (or toe) for OECD countries (IEA, 2000a) and non-OECD countries (IEA, 2000b), along with statistics on energy prices and taxes by fuel and by country in US dollars per toe (IEA, 2001). A problem with these data is that the ROAD sector defined in IEA energy balances includes trucks and commercial transport. This procedure leads to overestimation of the OS_r coefficients. Canada gives detailed data on fuel consumption in transportation. There, households represent 77% of total expenditure on road fuels (93% of road gasoline and 28% of road diesel). Adjusting the IEA data for the road sector using these coefficients on road fuels for Canada suggests that the error introduced is relatively small. For example, the OS_r coefficient from the country level data for Canada results in an OS_r value of 92% compared with an estimate relying just on the IEA data of 93.7%. In the United States, the share of refined oil products for own-supplied transportation in total household expenditure is estimated from statistics of the U.S. Department of Commerce to be 90%, compared to 94.8% with IEA data. These results indicate that IEA data may be considered as a relatively good proxy for OS_r. In cases where other additional data were not available we used the IEA data without adjustment.

The data for final purchases of vehicles (AC_r) can be taken directly from the GTAP Motor Vehicle (MVH) sector sales to final consumption. From these data and GTAP final consumption we can derive the value of total consumption of own-supplied transportation for each country/region and expenditure on vehicles and fuels.

The other operating costs (OC_{ir}) are derived as a residual of the total value of own-supplied transport less expenditure on vehicles and fuels. To disaggregate this quantity to the GTAP level a further identification of the supplying sectors of these other operating costs would be needed because the operating cost data are divided among the TRD sector (sales, maintenance, repair of motor vehicles, and trade margin on sales of automotive fuel are part of this sector), the ISR sector (insurance), and an OBS sector (which includes renting of transport equipment). As implemented in EPPA, however, these GTAP sectors are aggregated, and so we assume that OC_{ir} is supplied by the service (SERV) sector.

As is evident from the above discussion, for some countries there are multiple sources of data that provide the ability to cross-check results, while for other countries data are more limited and further assumptions are needed. In general, we used household expenditure data directly when available, but often checked these with physical energy data or price-quantity data. We converted expenditure data to shares and applied these shares to the expenditure totals in GTAP to avoid inconsistencies in currency conversion and between the original data sources and GTAP.

As noted earlier, the EPPA model uses a nested CES structure to describe consumer preferences as well as production, as this specification is compatible with the MPSGE solver. Figure 9.2 shows the household sector as it existed in EPPA without disaggregation of own-supplied transportation. The nesting structure aggregates all Armington goods into a single consumption good, which is then aggregated with savings to determine the level of consumer utility. Savings enters directly into the utility function, which generates the demand for savings and makes the consumption-investment decision endogenous. The central values for elasticities in the household sector are provided in Table 9.4. The elasticity between non-energy inputs to consumption is a function of per

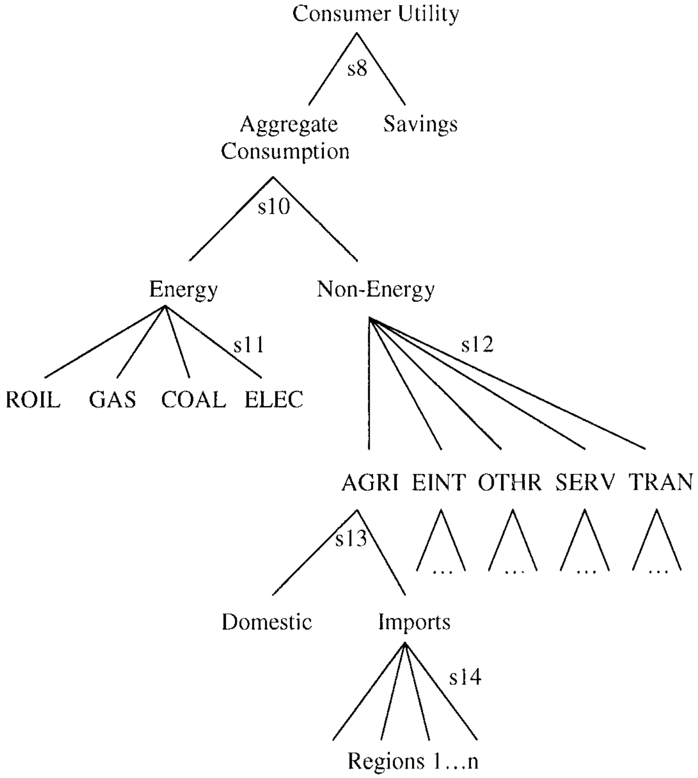

Figure 9.2. Structure of the household sector without transportation

capita income and thus varies by region and time period. Consumption shares also are function of per capita income.[1]

Figure 9.3 illustrates the addition of the own-supplied transport nest. As described above, we reallocate a portion of other industries (OTHR), services (SERV), and refined oil (ROIL) consumption to own-supplied transportation. The TRAN sector, which represents purchased transportation, is separated from the non-energy bundle in consumption. As shown in Figure 9.3, we rename purchased transportation as PURTRN sector and move it to the nest that represents a trade-off between purchased and own-supplied transportation (OWNTRN). The own-supplied

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[1] This specification allows use of the MPSGE algorithm, which was designed for the homogeneous CES family of production functions (homogenous of degree 1) while still capturing the changing structure of consumption with economic development that could not otherwise be represented using this functional form. For more details on the estimated relationship and its effects on emissions, see Lahiri, Babiker and Eckaus (2000).

Table 9.4. Elasticity of substitution values for the household sector

Notation	Elasticity	Value
s_8	between Aggregate Consumption and Savings	1
s_{10}	between Energy and Non-Energy Consumption	0.25
s_{11}	between Energy Inputs to Consumption	0.4
s_{12}	between Non-Energy Inputs to Consumption	0.25 – 0.65
s_{13}	between Domestic Goods and Imports	3
s_{14}	between Imports from different regions	5

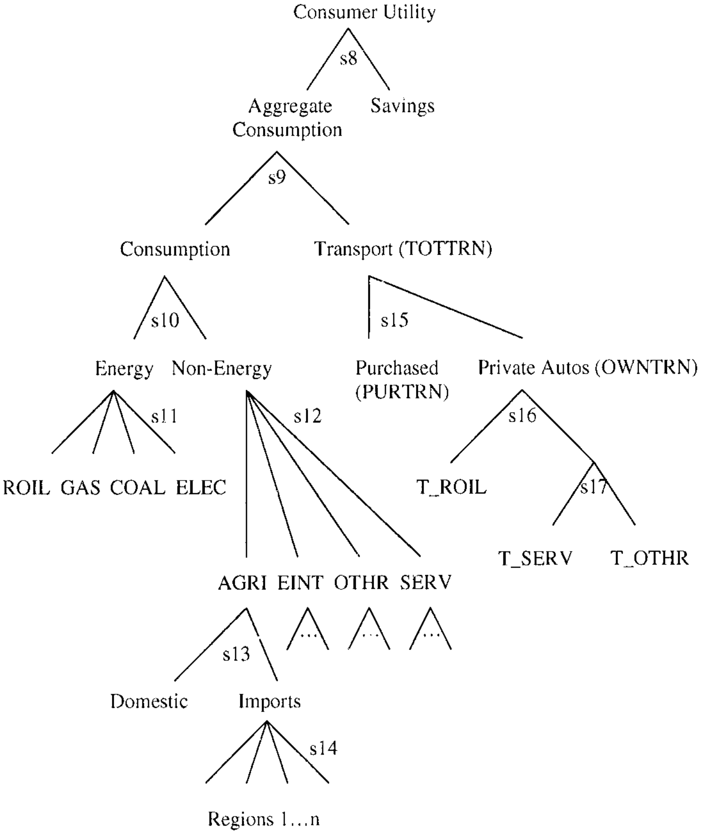

Figure 9.3. Structure of the household sector with transportation

transportation is aggregated from the consumption of other industries (T_OTHR), services (T_SERV), and refined oil (T_ROIL) directly re-

Table 9.5. Elasticity of substitution values for household transportation

Notation	Elasticity	Value
s_9	between Aggregate Consumption and Transport	0.5
s_{15}	between Own-Transport and Purchased-Transport	0.2
s_{16}	between Fuel and Other Inputs to Own-Transport	0.3 – 0.7
s_{17}	between Services and Other Inputs to Own-Transport	0.5

lated to private cars. The values for elasticities of substitution in the household transportation sector are provided in Table 9.5.

A sensitivity analysis of these elasticities is reported in Paltsev et al. (2004a). It is shown there that the results are insensitive to the elasticity of substitution between services and other inputs (s_{17}), and modestly sensitive to the elasticity of substitution between transport consumption and other consumption (s_9) and between purchased and own-supplied transport (s_{15}). But results are very sensitive to the elasticity between fuel and other inputs to own-supplied transport (s_{16}). The insensitivity of results to the own- and purchased-transportation elasticity was unexpected, but is easily explained. An economy-wide climate policy affects energy costs in both the purchased and own-supplied transport sectors, and upon inspection we found that the fuel shares of purchased and own-supplied transport were not very different. Thus, the policy created very little change in the relative prices of purchased and own-supplied transportation, so the elasticity of substitution was largely irrelevant. Other policy designs that differentially focused on automobiles and other transport modes could show greater sensitivity to this elasticity.

3. Flow and stock accounting of vehicles

The approach so far outlined is consistent with National Income and Product Account practices that treat most household purchases of durables, and vehicles in particular, as a flow of current consumption. In reality, of course, vehicles are capital goods that depreciate over time and provide a service flow over their lifetime. To reconstruct the data in this way would require further estimation of annual service flow, depreciation rates, and treatment of vehicle purchase as an investment. In industrial sectors, the residual of the value of sales less intermediate input and labor costs is an estimate of payments to capital, and under the assumption of a normal rate of return and depreciation rate these quantities imply a level of the capital stock. Own-supply from the household sector is not marketed, however, and thus there are no comparable sales data on gross value of the service from which intermediate input costs can be subtracted. An implicit rental value for the vehicle service could be constructed with historical data on vehicle sales, assumed depreciation rates, and an assumed rate of return following a Jorgenson (1987) type cost of capital accounting. Long-term car leasing rates could also be used as a basis for comparison, although these data may not be representative of the entire vehicle stock when new vehicles are typically leased for a 3-year period and then sold. Moreover, data on real leasing costs are not completely transparent because they depend on features of the lease — such as limits on mileage, additional payments if mileage limits are exceeded, and the purchase terms at the end of the lease.

At issue, given these more or less problematic approaches to estimation, is whether a significant effort to correctly account for the stock nature of vehicles would have a large effect on the results. Two issues arise. One is whether this re-accounting of the service flow would result in a large change in the fuel and vehicle cost shares. Estimating the correct relative cost shares is important because they affect the relationship between substitution elasticities and more-frequently-estimated own-price elasticities of demand, and the share values can affect the response to policies or fuel prices. A change that resulted in a much higher (lower) relative fuel share would mean that a given change in the fuel price, due to a carbon charge for example, would create a larger (smaller) percentage increase in the service cost, and thus make results more (less) sensitive to the ability to substitute away from own-supplied transportation toward purchased transportation or other goods. A second issue is the explicit treatment of irreversibility of investment in a dynamic model and how it might limit substitution away from fuels in the short-run.

3.1 The cost shares

Regarding shares, available evidence suggests the fuel share we have calculated for the GTAP dataset, based on the above information, is approximately consistent with estimates derived from total annualized costs of vehicle ownership with conventional cost components included. In the US, for example, the American Automobile Association (AAA) estimates the average annual cost of owning a vehicle including depreciation.[2] Assuming 10,500 miles per year per vehicle,[3] and using the AAA

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[2] See, http://www.hfcu.org/whatsnew/hff/june98_1.htm.

[3] This is an average annual mileage per vehicle based on EPA data on mileage by vehicle age class (EPA, 2002). Mileage of each vehicle age was weighted by the share of that age class

per mile estimate, would mean that fuel and oil costs were about 10% of total annual costs of owning and operating a car in 1998. Fuel alone at 10,500 miles per year, 23 mpg, and $1.20/gal would be 8.5% of total costs. While we do not expect to match these estimates exactly, they are comparable to the 8% fuel share we have estimated from the above procedure in our augmented GTAP data for the US.

We do not have comparable estimates for other regions, but our calculation of their fuel shares sometimes differs substantially. For the EU, for example, it is 24%, three times the US share. The big difference is that high fuel taxes raise the price of fuel in the EU. Using the AAA data and assuming 10,500 miles per year and 23 mpg, the fuel share rises to 24% with fuel at $4.00/gal, a price representative of fuel costs inclusive of taxes in Europe, and matches exactly our estimate based on GTAP data.[4] These calculations show that the tax-inclusive fuel price can explain the very different fuel cost shares in the EU and the US, and suggests that our approach for augmenting the data produces reasonable estimates. Of course, other costs and assumptions such as annual mileage or miles per gallon likely vary somewhat. One thing to note is that the AAA ownership costs include an estimate of financing costs based on a 20% down payment. Inclusion of financing costs is consistent with market data in GTAP and survey data on household expenditure that we used.

3.2 Capital accounting

Next is the issue of the treatment of capital vintaging in static and recursive-dynamic models. Note that, with no explicit stock of consumer vehicle capital, it is not possible to incorporate the vintaging that is imposed in EPPA in the industry production sectors. When vintaging is not represented, simulation studies often approximate the influence of fixity of capital through the choice of the value of the elasticity of substitution, using lower elasticities to estimate short-run effects of price changes, and raising the elasticity if one is interested in results closer to a long-run equilibrium after the capital stock has had time to adjust. Schäfer and Jacoby (2003) compared the representation of transport in an earlier EPPA version (EPPA3) with the results of a detailed MARKAL-based

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in the US total vehicle fleet (e.g., the annual mileage of cars falls as they age but older cars account for a much smaller share of the fleet as more and more of the age class is retired). We focused on light duty gasoline vehicles for the average mileage estimate, but the average for other classes would be very similar.

[4] In France, the share of fuel costs has decreased from 28% in 1985 to 21% in 1998; In 2000, the fuel share was 20% with cars estimated to consume 7.4 liter per 100 km , or 32 mpg, and to travel 8625 miles per year (Baron, 2002).

transport model that treated vehicle stocks explicitly. They found that reference EPPA elasticities over-estimated responses compared with the detailed model, especially in the near term. To correct for the lack of an explicit treatment of personal transport, they lowered the elasticities in near term periods and raised them in more distant periods.

The logic behind this application of greater substitution potential in the longer run is compelling. A possible limit for the specific elasticities estimated by Schäfer and Jacoby (2003), however, is that they focused on new vehicle technology and not in any detail on substitution among existing models and features. For example, their method misses the option to purchase a smaller vehicle or the same vehicle with a smaller engine, and omits the potential ability of consumers with multiple vehicles to shift their driving toward the more efficient ones. Many econometric studies of gasoline demand and vehicle travel have been conducted over the years (e.g., Archibald and Gillingham, 1981; Dahl and Sterner, 1991; Haughton and Sarker, 1996; Greene, Kahn and Gibson, 1999). In these studies the estimated response to price usually includes both a technical efficiency effect and a behavioral response in terms of miles driven.

To relate these different approaches to one another, and to pure technology studies, it is useful to observe that gasoline demand, denoted $F(p)$, can be defined as energy efficiency, e, times the number of miles traveled, M:

$$F(p) = e(p)M(p), \tag{9.4}$$

where both e and M are a function of fuel price p. Logarithmic differentiation of (9.4) with respect to the price of gasoline yields:

$$\frac{\partial \ln F}{\partial \ln p} = \frac{p}{e}\frac{\partial e}{\partial p} + \frac{p}{M}\frac{\partial M}{\partial p}. \tag{9.5}$$

And recognizing the expressions for elasticities, we can rewrite (9.5) as:

$$\eta_{F,p} = \eta_{e,p}\eta_{M,p}, \tag{9.6}$$

where $\eta_{F,p}$ is the elasticity of gasoline demand to a change in fuel price, $\eta_{e,p}$ is the elasticity of energy efficiency (e.g., miles per gallon) with respect to a change in p, and $\eta_{M,p}$ is the elasticity of vehicle miles with respect to a change in p.

The version of the bottom-up MARKAL model applied by Schäfer and Jacoby (2003) assumes implicitly that $\eta_{M,p} = 0$. Also, their computation of $\eta_{F,p}$ takes into account the effect of fuel price change only on vehicle technology — capturing the fact that an increase in fuel price will speed up the penetration of vehicles of more efficient design, resulting in lower energy demand. This focus on technology shift likely underestimates the efficiency elasticity, as it does not consider the effects of a change in fuel price by means of substitutions among existing car models/options and/or through changes in driver behavior. For example, new car consumers face choices among vehicle sizes and engine power even within a particular technology class. At higher fuel prices owners might also perform better maintenance on their cars to increase efficiency (e.g., tune-ups, maintenance of tire pressure, etc).[5]

Greene, Kahn and Gibson (1999) estimated a pure behavioral response in terms of miles driven, treating any change in energy efficiency (defined as gallons of fuel per mile) as *exogenous* and estimated the US the long-run fuel price elasticity of vehicle miles travel ($\eta_{M,p}$) to be in the range of -0.2 to -0.3. Combining this result with an efficiency elasticity ($\eta_{e,p}$) of -0.126 estimated from the MARKAL model suggests an own-price elasticity of gasoline demand ($\eta_{F,p}$) of between -0.3 to -0.4. Because the MARKAL model used by Schäfer and Jacoby (2003) does not consider all the possibilities for increasing efficiency this might be considered a low estimate. Table 9.6 shows that the use of different data and/or methods can create crucial differences in the magnitude of gasoline price elasticity. Nevertheless, the overwhelming evidence from this survey of econometric studies suggests that the short run price elasticity typically falls between -0.2 to -0.5, and long run price elasticities will typically tend to fall in the -0.6 to -0.8 range (see Graham and Glaister, 2002).

We can approximately translate own-price elasticities of gasoline demand to the substitution elasticity of the CES production function via the formula (Hyman et al., 2003):

$$\sigma_{F,p} = -\frac{\eta_{F,p}}{1-\alpha_F}, \tag{9.7}$$

where $\sigma_{F,p}$ represents the constant elasticity of substitution between energy and other inputs, $\eta_{F,p}$ stands for the own-price elasticity of fuel demand, and α_F is the cost share of fuels in the production function. From household budget data described in Section 2, α_r is about 0.08 percent in the US. Using Equation (9.7), based on the own-price elasticity range in Table 9.2, the short run substitution elasticity is between 0.22 to 0.54 and the long run substitution elasticity is 0.65 to 0.87 in the US.[6]

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[5] Other versions of MARKAL can explore the effect of differential maintenance and choice of auto size for given technology, but other than sensitivity testing of the effect of alternative assumptions about the share of cars and light trucks (i.e., pickups, vans, SUVs) these features were not included in the analysis by Schäfer and Jacoby.

[6] In the EPPA model, we gradually increase elasticity of substitution between fuel and non-fuel inputs in the household transportation sector from 0.3 to 0.7 over a century.

Table 9.6. Survey of econometric studies on gasoline price elasticity

Authors	Country or region	Gasoline price elasticity SR	LR	Type of data
Drollas (1984)	UK	−0.26	−0.6	Country data, 1950–1980
	West Germany	−0.41 to −0.53	−0.8 to −1.2	
	France	−0.44	−0.6	
	Austria	−0.34 to −0.42	−0.8 to −0.9	
Sterner et al. (1992)	Canada	−0.25	−1.07	Country data, 1960–1985
	US	−0.18	−1	
	Austria	−0.25	−0.59	
	Belgium	−0.36	−0.71	
	Denmark	−0.37	−0.61	
	Finland	−0.34	−1.1	
	France	−0.36	−0.7	
	Germany	−0.05	−0.56	
	Greece	−0.23	−1.12	
	Ireland	−0.21	−1.62	
	Italy	−0.37	−1.16	
	Netherlands	−0.57	−2.29	
	Norway	−0.43	−0.9	
	Portugal	−0.13	−0.67	
	Spain	−0.14	−0.3	
	Sweden	−0.3	−0.37	
	Switzerland	0.05	0.09	
	UK	−0.11	−0.45	
	Australia	−0.05	−0.18	
	Japan	−0.15	−0.76	
	Turkey	−0.31	−0.61	
	Mean	−0.24	−0.79	
Dahl & Sterner (1992)	OECD	−0.26	−0.86	Country data, 1960–1985
Eltony (1993)	Canada	−0.31	−1.0073	Micro-level data, 1969–1988
Goodwin (1992)		−0.27	−0.71	Time-series
		−0.28	−0.84	Cross-section
Johansson & Schipper (1997)	12 OECD		−0.7	1973–1992
Puller & Greening (1999)	US	−0.35	−0.8	US household data
Agras & Chapman (1999)	US	−0.25	−0.92	Annual US data. 1982–1995
Haugton & Sarkar (1996)	US	−0.09 to −0.16	−0.22	Annual US States data
Nivola & Crandall (1995)	US	−0.1 to −0.4	−0.6 to −1.1	US data
Graham & Glaister (2002)	US	−0.2 to −0.5	−0.23 to −0.8	
	OECD	−0.2 to −0.5	−0.75 to −1.35	

Table 9.6 (continued)

Authors	Country or region	Gasoline price elasticity SR	LR	Type of data
Hagler Bailly (1999)	Canada	−0.1 to −0.2	−0.4 to −0.8	

Sources: based on Graham & Graister (2002); Nivola & Crandall (1995); Haugton & Sarkar (1996); Agras & Chapman (1999); Hagler Bailly (1999).

3.3 Other issues

Modeling the household production of transportation service raises other issues that we mention briefly here as directions for future investigation, and as caveats to the use of our formulation. For example, consider Figure 9.4 and what other factor inputs, represented by the box labeled A, might appropriately enter household production. First, consistency of treatment of returns to capital in the household sector would attach an opportunity cost of funds invested in automobiles as a payment to the capital "lent to" production of own-supplied transport services. Only financing costs paid to lending firms are currently included as a flow to the services sector. The value of any cash payments for vehicles, or the value of the vehicle once loans are paid off, incurs no such cost in the model when in reality there is an opportunity cost of the capital in lost investment income or continued interest charges on other loans. Similarly, market data do not account for any household supplied parking and vehicle storage costs (e.g., garage, driveway, park-

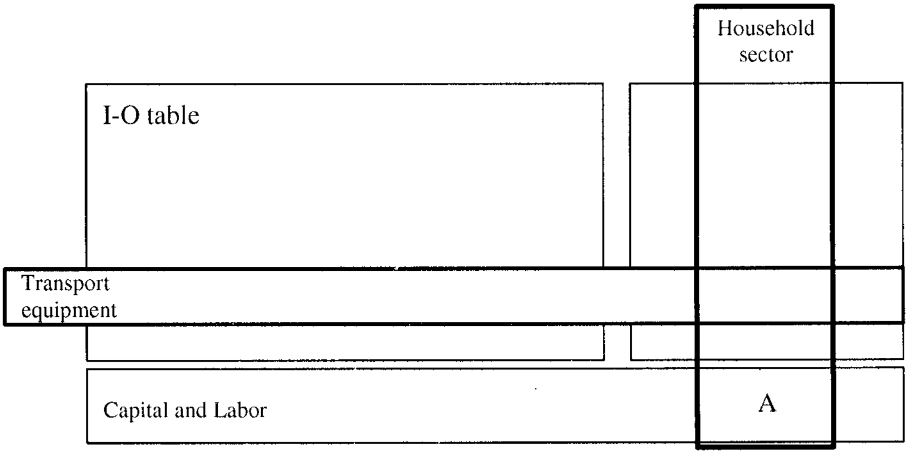

Figure 9.4. Household production of transportation, broader considerations

ing areas owned by the household). A full-cost accounting of automobile ownership and use would apply a rental cost to the own-supply of transportation services and a corresponding payment to the household for the capital. Where the household rents a dwelling, some part of that rental may be correctly attributed to the own-supply of transportation services if garage/parking areas are provided along with the housing rental.

One might also consider including a labor cost both in own-supply and purchased transportation to account for travel time. Such a fuller accounting of household labor input could be important in explaining and projecting modal shifts as wages or fuel prices change. Detailed transportation surveys suggest travel time as an important explanatory variable for travel mode choice (Schäfer and Jacoby, 2003). To accurately model this process would likely require further disaggregation of purchased transportation and own-supplied services. For example, for the daily work trip automobiles may have a time advantage in competition with public transportation, but for long-distance travel automobiles have a time disadvantage compared with air or rapid rail travel.

Adding these costs and income flows to households would expand the accounts beyond what is currently included in the market economy as part of GDP, consumption, and income, but such a change would more fully consider the full cost of vehicle ownership and real differences between own-supplied and purchased transportation services. Public supply of highway infrastructure and maintenance of it ought also to be accounted for. In the US, fuel taxes largely support highway construction. We have included them as part of the price of fuel. They thus have no distortionary effect but we have not treated the public sector as explicitly providing this good to own-supplied transportation. Additionally, one might be concerned about other non-market costs of transportation such as contribution to air pollution. We mention these issues as possibilities for further research and data development but have not pursued their potential importance beyond the brief discussion here. To implement them would require considerable effort to estimate or approximate these additional costs, for which data are not readily available, and which would require more elaborate modifications and adjustments to GTAP.

4. Exempting transportation from greenhouse gas control measures

To study the effect of exempting transport from a carbon policy we focus on two regions which represent a wide range of pre-existing fuel taxes. Table 9.7 provides the GTAP tax rate structure for refined oil use by households and industrial transport in several regions. USA tax rates

Table 9.7. Fuel tax rates

	USA	EUR	CAN	JPN	ASI	AFR
Tax Rate on Household Demand for ROIL	0	4.7	1.3	2.7	0.3	0.4
Tax Rate on Industrial Transport Demand for ROIL	0	2.5	0.7	0.9	0.07	0.2

are reported as zero here because we assume the existing transport fuel tax ($0.184 per gallon) is a user charge covering highway construction. The tax revenues are designated for highway repair and construction through the Federal Highway Trust Fund. The European tax rates for fuel used in transportation are the highest in the world. The revenues from these taxes have no specific designation, but instead are part of general revenue. They may correct in part for non-climate-related external effects of fuel use — such as air and noise pollution, congestion, or other spillovers — but there is scant evidence that this purpose reflects a substantial fraction of prevailing tax levels (Babiker, Reilly and Viguier, 2004; Newbery, 1992). We thus treat them as tax distortions rather than as a user charge. The actual rates vary somewhat among EU countries, fuels, and sectors but were generally in the range of $2.80 to $3.80 per gallon for gasoline (OECD/IEA, 2004).

In terms of the shares of carbon emissions from transportation, the USA and Europe are about the same. From Table 9.8, industrial and household transportation emissions add up to 25.1 per cent of total emissions in USA and 26.4 per cent in Europe. The similar if somewhat larger share of transport emissions in Europe is at first surprising, because the high fuel taxes in Europe should lead to less vehicle use and more ef-

Table 9.8. Sectoral CO_2 emissions share (%)

	USA	EUR
AGRI	2.9	1.8
ROIL	2.7	3.3
ELEC	40.8	28.6
EINT	12.3	16.4
OTHR	3.0	4.0
SERV	9.5	11.5
Industrial TRAN	12.7	12.3
Household TRAN	12.4	14.1
Household	3.8	7.9

ficient vehicles, as suggested by our elasticity estimates. In fact, the similar share in the USA and Europe is not inconsistent with greater vehicle efficiency and less vehicle use. The reason for the similar emission shares is that the US is more carbon intensive across the economy, primarily because of the heavy reliance on coal in electric utilities. With emissions comparatively higher in the rest of the economy, the heavy use of vehicles and relatively inefficient fleet still leads to no greater share of economy-wide emissions in the US than in Europe. The fact that the shares are similar between the regions means that, in both regions, the exemption of transportation from an emission cap will impose a large (and similar) additional reduction burden on the sectors that remain capped.

To estimate the welfare costs of exempting industrial and household transportation sectors from a carbon policy, we consider a scenario where, starting in 2010, a region limits its carbon emissions to 25% below the 2010 non-policy level, and holds that absolute constraint to 2025. We construct the following cases, imposing this restriction individually on the US and on Europe.

Ref. Reference case with no carbon policy
Case 1. 25% reduction, with economy-wide emissions trading
Case 2. 25% reduction, with no emissions trading among sectors
Case 3. As in Case 1, with industrial transport excluded from the restriction
Case 4. As in Case 1, with household transport excluded from the restriction
Case 5. As in Case 1, with both industrial and household transport sectors excluded

No international trade in emissions is allowed. There is some policy effect on goods trade, which is included in the model, but its influence on the results shown here is insignificant.

The reference case serves as a basis of comparison, to allow estimation of the welfare cost of the policy cases. In Case 1 all sectors within each economy are allowed to trade their carbon emissions. In Case 2 all sectors take an equal share of the emissions reduction without any possibility of emission trading with other sectors. In Cases 3 to 5 non-excluded sectors participate in emission trading, while excluded sectors have no limit on their carbon emissions. In Cases 3 to 5 we require that the economy continue to meet the overall target reduction. Exclusion of one or more sectors thus means that the remaining sectors must further reduce their emissions to make up for in the excluded sectors.

Table 9.9 reports the results for the US, and Table 9.10 contains results for Europe. In both regions, the policy including economy-wide

Table 9.9. Change in welfare in USA (%), economy-wide emissions held 25% below 2010 baseline level

	Case 1	Case 2	Case 3	Case 4	Case 5
	Economy-wide trading	Sectoral targets, no trading	Industrial transport exempt	Household transport exempt	All transport exempt
2010	−0.23	−0.26	−0.31	−0.30	−0.41
2015	−0.38	−0.45	−0.52	−0.49	−0.67
2020	−0.53	−0.69	−0.72	−0.68	−0.94
2025	−0.71	−1.02	−0.98	−0.91	−1.27

Table 9.10. Change in welfare in Europe (%), economy-wide emissions held 25% below 2010 baseline level

	Case 1	Case 2	Case 3	Case 4	Case 5
	Economy-wide trading	Sectoral targets, no trading	Industrial transport exempt	Household transport exempt	All transport exempt
2010	−1.33	−1.83	−1.36	−1.01	−0.99
2015	−1.75	−2.62	−1.79	−1.37	−1.35
2020	−2.30	−3.59	−2.36	−1.81	−1.76
2025	−2.81	−4.78	−2.90	−2.23	−2.19

emissions trading (Case 1) is less expensive for all years than the imposition of independent sectoral caps (Case 2). Differential growth in emissions among sectors, and differential opportunities to reduce emissions, mean there is some benefit from emissions trading. The specific benefit of trading depends, of course, on the sectoral allocation. In some allocation schemes there is an attempt to consider projections of growth for sectors, or opportunities to abate emissions. If projected exactly, sectoral caps could achieve the emissions trading result, and there would be no benefit from trading. The presumed superiority of emissions trading in terms of economic efficiency, however, is that trading can correct for our inability to project emissions with accuracy. With trading, such errors in projection do not lead to loss of economic efficiency. More generally, the simple case for trading is that economic efficiency is separated from the problem of how to allocate emissions, leaving that decision to be made on other grounds.[7] It is noteworthy that the percentage welfare loss in Europe is considerably greater than in the US, a result to which we will return.

For the US, Cases 3 – 5 (which exempt the transportation sectors) lead to increased carbon tax rates for remaining sectors and higher welfare costs for the economy as a whole. Case 5 is the most costly, exempting sectors that account for 25% of emissions, and thereby requiring proportionally greater reductions in the other sectors. This exemption roughly doubles the economy-wide welfare loss over the period 2010 to 2025. Even though industrial and household transportation contribute a similar share of emissions for the US, we find that the industrial transportation exemption increases the policy cost slightly more than the household transportation exemption.

The European results for Cases 3 – 5 (Table 9.10) show that exempting the transportation sectors, or even just the household transport sector alone, serves to *reduce* the economy-wide cost of the restriction. The result is counter-intuitive: limiting flexibility and forcing greater reductions on a narrower part of the economy should under most circumstances increase cost. In fact, we do find that the carbon prices rise in the exemption cases compared with Case 1. But costs measured in terms of lost economic welfare fall if household transport is exempted. This result occurs because climate policy designed to limit carbon emissions affects fuel cost, and fuels in Europe (and most particularly the gasoline that dominates household use) are already taxed at a high rate. There is thus a two-part effect: a direct cost of the emissions restriction and a distortion cost caused by the interaction of that restriction with existing fuel taxes (and this distortion cost is removed or decreased in the exemption cases). Paltsev et al. (2004b) describe in more detail how the general equilibrium economic effects of a policy can differ from a simple marginal abatement curve analysis. Comparing the USA, where exemptions of transportation increased the cost of restriction, to the European results where exemptions can actually reduce the cost, we can infer that the tax interaction effect is a significant cost.

An initial reaction to these results is surprise that the tax distortion effects are so large that avoiding them reduces cost, even when far deeper cuts must be made in the sectors that remain under the cap. Figure 9.5 illustrates how the distortion costs can be so large. We show a demand for fuel, assuming a supply at constant marginal cost, yielding a price

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[7] The more complex case of allocating permits versus selling and using the revenue to offset existing distortionary taxes is one well-recognized caveat to this simple result. See, e.g., Babiker, Metcalf, and Reilly (2003).

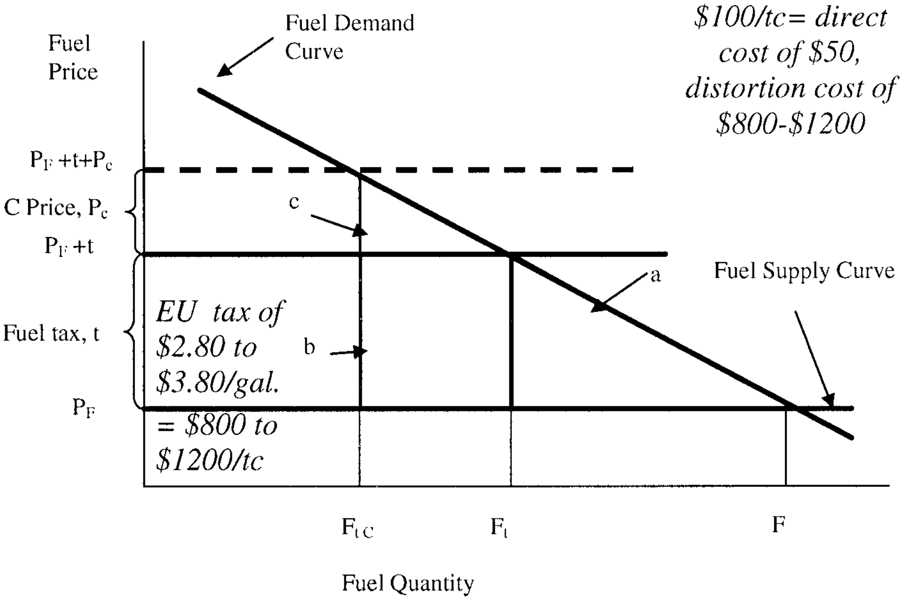

Figure 9.5. Effects of tax and carbon policy interactions on carbon policy costs

of fuel (p_f). The existing fuel tax (t) results in the tax-inclusive price of fuel of $p_f + t$. The economic cost of fuel tax policy is the triangle labeled a. A carbon cap results in a carbon price labeled P_C. The fuel price (tax and carbon price inclusive) is thus $p_f + t + P_C$. As shown by Paltsev et al. (2004b) a marginal abatement curve cost approach evaluates the carbon policy cost as the triangle labeled c. But, the full cost of the policy includes the tax interaction loss represented by the rectangle labeled b. Fuel taxes in Europe which for gasoline are on the order of \$2.80 to \$3.80 per gallon. Given the carbon content of gasoline this equates to a carbon tax equivalent of \$800 to \$1200 per ton C. Considering a carbon policy that resulted in a carbon price of \$100 per ton C, which is the approximate level of carbon tax we obtain in these simulations, the direct cost per ton is the triangle area, $\frac{1}{2} * \$100 = \$50$. But the tax interaction effect is a rectangle. For one ton this is $1 * \$800$ (or up to \$1200). Thus, in the transport sector the distortion cost in Europe is on the order of 16 to 24 times greater than the direct carbon cost. Thus, it is not hard to see how avoiding the tax distortion cost by exempting transportation saves more than the increased cost on other sectors because they must reduce emissions further.

The results presented in Tables 9.9 and 9.10 show how the interplay between carbon policies and pre-existing taxes can differ across countries.

It is important to represent these tax distortions, and other ways in which real economies differ from the idealized textbook economy. In this case, distortions increase the cost, and exempting sectors in Europe avoided these added tax interaction effects. In general, the interaction of policies with taxes or other economic distortions can either increase or decrease the policy cost. As this comparison between the US and Europe shows, one must be cautious in extrapolating the results from a country specific analysis to other countries.

5. Conclusions

In order to model the household transportation sector explicitly, we have created a methodology based on the use of the GTAP system and additional data for household expenditures on own-supplied transport by region. The surveys report that household expenditures of own-supplied transport are about 10 percent of total household expenditures, and refined oil expenditures in household transportation are on the order of 90 percent of total household oil use. Based on the developed methodology, we have modified the household transportation sector in the EPPA model. As shown in Paltsev et al. (2004a) and Schäfer and Jacoby (2003) it is possible to capture the broad behavior of a disaggregated model with a more highly aggregated model if one adjusts the elasticity parameters to match the disaggregated model. But, it is hard to know what the correct parameters for the aggregate model unless one can extensively compare performance of the aggregate model with the detailed models or directly to relevant econometric results. That alone makes a case for disaggregating key sectors of the economy.

Here we explored another important reason for greater disaggregation. Tax interaction effects can be important, and with differential tax rates across sectors it is necessary to maintain sufficient disaggregation to represent this variation. The magnitude of the possible effects is demonstrated for a set of cases that exclude industrial and household transport from a carbon policy. In the absence of pre-existing distortions, as is the case in the US, exemption of transportation sectors implies increased carbon tax rates for other sectors and higher costs for an economy as a whole. With existing distortions, as with high transport fuel taxes in Europe, the policy interaction effects are important in estimating costs. We showed that exemption of the already highly taxed transport sector actually decreases the estimated cost of meeting a carbon constraint, even when the capped sectors are required to cut further to make up for the sector exemptions. The disaggregation of household transportation sector thus allows better use to be made of the extensive work done on the transportation sector and the substitution possibilities it offers. By disaggregating the transport sector and being able to select elasticities that more accurately characterize its substitution possibilities we have been able to more accurately characterize the economic costs of a sample policy for greenhouse gas reduction.

Acknowledgments The CGE model underlying this analysis was supported by the US Department of Energy, Office of Biological and Environmental Research [BER] (DE-FG02-94ER61937) the US Environmental Protection Agency (X-827703-01-0), the Electric Power Research Institute, and by a consortium of industry and foundation sponsors.

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Chapter 10

PRICING AND TECHNOLOGY OPTIONS: AN ANALYSIS OF ONTARIO ELECTRICITY CAPACITY REQUIREMENTS AND GHG EMISSIONS

Pierre-Olivier Pineau
Stephan Schott

Abstract Many jurisdictions face the problem of having to reduce GHG emissions and new electricity capacity requirements.Ontario has the additional commitment of phasing out its coal power plants. Time of use (TOU) pricing is seldom considered as an option in the analysis of these problems, even if its impacts on capacity requirements and emissions can be substantial. We analyze to what extent TOU pricing can reduce capacity requirements and we evaluate its impacts on total energy use and CO_2, SO_2 and NO_x emissions under different technologies. We also introduce "transfer of demand" between peak and off-peak periods to account for cross-price elasticity between time periods.

1. Current Ontario electricity context: GHG emissions and capacity constraints

In 2001, Canada emitted 720 megatonnes (Mt) of CO_2 equivalent[1] (EC, 2003a). Under the Kyoto protocol, Canada has to reduce its emissions to 6% under the 1999 level (607 Mt) in the period from 2008 to 2012.[2] Based on the 2001 emission level, this adds up to approximately 150 Mt of emissions that Canada has to cut. The province of Ontario emitted 201 Mt in 2001 (EC, 2003a), with the electricity sector responsi-

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[1] CO_2 equivalent is "the amount of CO_2 that would cause the same effect as a given amount or mixture of other greenhouse gases" (EC, 2003b).

[2] See Government of Canada (2001) for a detailed description of Canada's commitment.

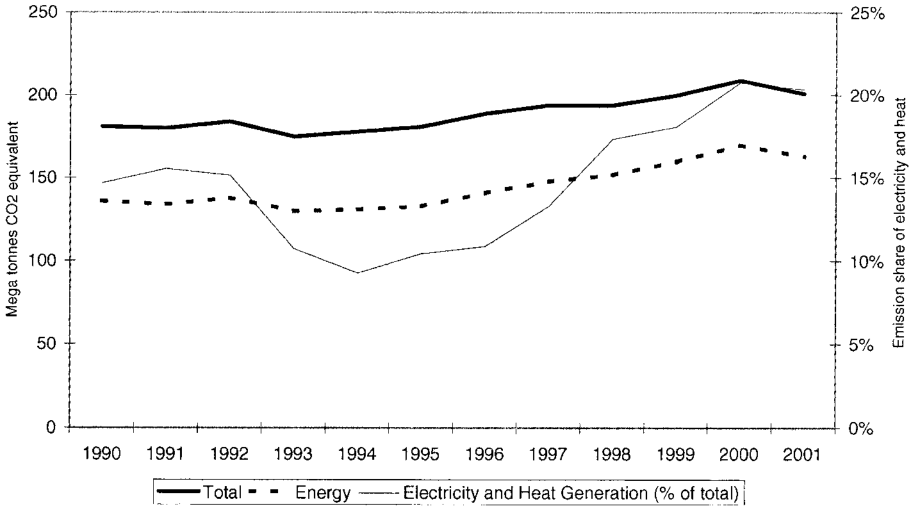

Figure 10.1. Ontario CO_2 equivalent emission and share of electricity (EC, 2003a)

ble for 20% of this amount, as Figure 10.1 shows. Reduction of emissions in the electricity sector can therefore make a significant contribution to the overall effort to reach the target.

Ontario had a total installed capacity of 30,501 MW in 2004 (IMO, 2004a). Its provincial government committed itself to shut down 7,500 MW of coal-fired generating stations by the end of 2007.[3] This creates a capacity constraint, amplified by the lack of investment since 1998 and by the uncertainties and temporary shutdown of some of the five nuclear generating stations (representing 10,831 MW of capacity, see Table 10.1). In 1998, the Ontario Electricity Act significantly reformed the electricity market by unbundling the electric utility (Ontario Hydro), by introducing an independently operated spot market, and by preparing the retail market for consumer choice. To face this capacity challenge, an Electricity Conservation & Supply Task Force (ECSTF) has been established to study different technology scenarios (ECSTF, 2004), where the two principal options identified are natural gas-fired generation and nuclear power.

Ontario, therefore, faces two distinct but interrelated challenges: (1) to reduce its greenhouse gas (GHG) emissions as part of the general Canadian effort to meet the Kyoto target, and (2) to add new generating capacity to meet its electricity supply needs.

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[3] See Legislative Assembly of Ontario (2004), Electricity Restructuring Act, Schedule A, article 32.

Table 10.1. Basic supply and demand side information — Ontario electricity sector

Supply Technology	Energy 2003	Capacity	Demand sector		TWh
Nuclear	40%	35.5%	Residential	33%	50.1
Thermal (Coal)	23%	24.8%	Commercial	34%	51.6
Hydropower	22%	25.1%	Industrial	33%	50.0
Other	15%	14.5%			
Total	151.7 TWh	30,501 MW			

Sources: ECSTF (2004), IMO (2004a,b), NEB (199, Appendix 3, Table A3.4a)

In this paper, we analyze how different technology and pricing choices can influence both of these challenges.We innovate by combining time of use (TOU) pricing, transfer of demand between peak and off-peak demand periods and emission pricing. The "transfer of demand" represents a cross-price elasticity effect that is seldom modeled in energy planning models, although its reality is well documented. We show that while TOU pricing for residential and commercial consumers may reduce capacity requirements, it increases total electricity consumption. Furthermore, when consumers transfer demand from peak to off-peak periods, TOU pricing has the effect of increasing capacity requirements. The increase in total consumption may be problematic if GHG emission targets have to be reached.We document the scope of this problem by looking at TOU pricing models with and without transfer of demand under different technologies, price elasticity assumptions and with and without the consideration of the cost of emissions (for CO_2, SO_2 and NO_x). We find that TOU pricing, under the nuclear investment option, can help to reduce capacity, energy consumption and emissions, while having only a limited impact on prices, particularly if consumers learn to transfer demand between periods. For new CCGT generation, average cost pricing coupled with emission pricing is an interesting option to limit GHG emissions.

2. Time of use pricing: modeling for analysis

Electricity sector models analyzing GHG emissions usually model demand as an inelastic quantity, supplied by least-cost dispatch (ICF Consulting, 2003) or with limited own-price information, such as in the *Market Allocation Model* (MARKAL) or the *Canadian Integrated Modelling System*(CIMS), see for instance NCCP-Analysis and Modelling Group (2000). An analysis of the impact of pricing options and price and cross-price elasticities at a micro-economic level is absent from the literature.This paper aims at contributing to the energy policy analysis by considering some of these issues. There is a real need to explore the possible impacts of TOU pricing and other pricing alternatives to go beyond the traditional average cost pricing structure. Indeed, while the pricing structure can have an important impact on demand, it is usually not considered in GHG reduction strategies for the electricity sector; see for instance NCCP-Electricity Table (1999), where only emission pricing is analyzed to act on emissions. Other pricing mechanisms such as TOU pricing can be used, however, especially if capacity reduction (or capacity increase limits) is simultaneously targeted, as it is currently the case in Ontario.

2.1 Model

We use a simple one technology, two demand period model of the electricity market, where capacity is set under a cost recovery constraint. Two different pricing schemes are analyzed: average cost pricing and TOU pricing.However, in the TOU pricing case, to account for the cross-price elasticity of demand between the periods, we introduce a *transfer of demand rate* from the peak period to the off-peak period.

Following Protti and McRae (1980) and Borenstein (2004), we use constant elasticity demand functions for the off-peak and peak periods. We introduce, however, different price elasticities for the two periods (the empirical justification for this is given later in Table 10.2):

$$Q_{\text{off-peak}} = aP^{b}_{\text{off-peak}} \tag{10.1}$$

$$Q_{\text{peak}} = ZaP^{\alpha b}_{\text{peak}} \tag{10.2}$$

$Q_{\text{off-peak}}$, Q_{peak}, $P_{\text{off-peak}}$ and P_{peak} are the quantities and prices in off-peak and peak periods respectively. The parameters $a > 0$ and $Z > 0$ scale the level of demand, with demand in peak period being a multiple of the demand in the off-peak period. The elasticity in the off-peak period is b, and the parameter $\alpha > 0$ scales the difference in price elasticity between peak and off-peak periods. The model, therefore, allows us to evaluate the effects of period-specific differences in price elasticity.

Capacity K is set to the hourly quantity demanded during the peak period, Q_{peak}, so that $K = Q_{\text{peak}}$ The fixed capacity cost is r (in \$/MW), while the constant production cost is c (in \$/MWh). With $0 < \omega < 1$ being the proportion of time where the market is in peak demand, the cost recovery constraint is:

$$(P_{\text{off-peak}} - c)(1-\omega)Q_{\text{off-peak}} + (P_{\text{peak}} - c)\omega Q_{\text{peak}} = rK. \tag{10.3}$$

Under this model of the market, we can find the prices under average cost and time of use pricing. For both cases, these prices can be interpreted as the price of the regulated utility under a cost recovery constraint. In the TOU pricing case, prices can also be interpreted as long-run competitive prices.

Average cost pricing Under average cost pricing, $P = P_{\text{off-peak}} = P_{\text{peak}}$, and

$$P = c + \frac{rQ_{\text{peak}}}{Q_{\text{off-peak}} + \omega(Q_{\text{peak}} - Q_{\text{off-peak}})} \tag{10.4}$$

Using the demand equations (10.1) and (10.2), P is the solution of the following nonlinear equation:

$$(P - c)\left(P^{b(1-\alpha)}(1 - \omega) + Z\omega\right) = rZ \tag{10.5}$$

Time of use pricing We model TOU pricing as marginal cost pricing in our two-period model. This leads to two possible solutions: the firm-peak case and the shifting-peak case (see Crew and Kleindorfer (1986)). In the firm-peak case, the full capacity K is only used during the peak demand period, in which fixed costs are fully recovered. During the off-peak period, as there is excess capacity, the price is equal to the cost of production c. This case is, therefore, characterized by the following equations:

$$K = Q_{\text{peak}} > Q_{\text{off-peak}} \tag{10.6}$$

$$P_{\text{peak}} = c + \frac{r}{\omega} \tag{10.7}$$

$$P_{\text{off-peak}} = c \tag{10.8}$$

In the shifting-peak case, the full capacity is used in both periods (hence the "shifting" peak, from one period to the other). Using the cost constraint (10.3), this case is characterized by the following equations:

$$K = Q_{\text{peak}} = Q_{\text{off-peak}} \tag{10.9}$$

$$P_{\text{off-peak}}(1 - \omega) + P_{\text{peak}}\omega - c = r \tag{10.10}$$

Using the demand equations (10.1) and (10.2) and equation (10.10), P_{peak} can be found by solving the nonlinear equation (10.11).

$$(1 - \omega)Z^{1/b}P_{\text{peak}}^{\alpha} + P_{\text{peak}}\omega - c = r \tag{10.11}$$

$P_{\text{off-peak}}$ is then deduced using (10.10).

Time of use pricing with transfer of demand Although cross-price elasticity between demand periods has been observed in many econometric studies (Taylor and Schwarz, 1990; Filippini, 1995a,b; Herriges et al., 1993; Patrick and Wolak, 2001), models of the electricity market usually assume the independence of demand across periods, in order to simplify their model (e.g., Borenstein (2004)).In our model consumers transfer demand from the peak to the off-peak period. An exogenous parameter $0 < \gamma < 1$ measures the proportion of demand transferred. We assume that the transfer is limited to situations where $P_{\text{peak}} > P_{\text{off-peak}}$. When the price in both periods is equal, no further transfer occurs. With transfer of demand, the demand equations for both periods are:

$$Q'_{\text{off-peak}} = aP^{b}_{\text{off-peak}} + \gamma ZaP^{\alpha b}_{\text{peak}} \tag{10.12}$$

$$Q'_{\text{peak}} = ZaP^{\alpha b}_{\text{peak}} - \gamma ZaP^{\alpha b}_{\text{peak}} = ZaP^{\alpha b}_{\text{peak}}(1-\gamma) \tag{10.13}$$

Two cases are again possible, the firm-peak case and the shifting-peak case. In the firm-peak case, prices are again equal to the marginal costs in both periods, as shown in equations (10.7) and (10.8). In the shifting-peak case, capacity will be used in both periods, and the price will be obtained by solving two nonlinear equations:

$$P_{\text{off-peak}} = Z^{1/b}P^{\alpha}_{\text{peak}}(1-2\gamma)^{1/b} \tag{10.14}$$

$$Z^{1/b}P^{\alpha}_{\text{peak}}(1-2\gamma)^{1/b}(1-\omega) + P_{\text{peak}}\omega - c = r \tag{10.15}$$

2.2 Results

Firm-peak or shifting-peak? It is of practical interest to be able to determine when a firm-peak or a shifting-peak will be obtained. By using the price information in a firm-peak case (equations (10.7) and (10.8)) and the demand functions (10.1) and (10.2), $Q_{\text{off-peak}}$ and K can easily be determined as a function of the demand and cost parameters. The condition $K > Q_{\text{off-peak}}$ requires the following condition to hold:

Firm-peak condition A

$$r < \omega\left[\left(\frac{c}{Z^{1/b}}\right)^{1/\alpha} - c\right] \tag{10.16}$$

Firm-peak condition A′

$$Z > \left[\frac{c}{(c + r/\omega)^{\alpha}}\right]^{b} \tag{10.17}$$

These equivalent conditions indicate the circumstances under which a firm-peak is observed as a function of exogenous parameters. A firm-peak is obtained when the fixed cost r is relatively small compared to the production cost c, weighted by demand parameters (right-hand side of (10.16)). Equivalently, a firm-peak is obtained when the peak demand parameter Z is larger than the RHS of (10.17). Otherwise, a shifting-peak is observed.When demand transfer occurs, similar firm-peak conditions exist:

Firm-peak condition B

$$r < \omega\left[\left(\frac{c^b}{Z(1-2\gamma)}\right)^{1/\alpha b} - c\right] \tag{10.18}$$

Firm-peak condition B′

$$Z > \frac{c^b}{(c + r/\omega)^{\alpha b}(1-2\gamma)} \tag{10.19}$$

Level of transfer needed to have equal prices in peak and off-peak demand With the increasing awareness of price differentials between peak and off-peak and the improvement of technologies to manage demand, consumers may be able to transfer more and more demand from the peak to the off-peak period.This increasing transfer would translate into a growing value for γ, the exogenous transfer parameter. Transfer, however, only occurs when there is a price differential (and as this differential becomes smaller, the incentive to transfer decreases — the details of these dynamics are, however, not modeled here). It is possible to identify the level of γ such that prices in the peak and off-peak periods are equal:

$$\gamma = \frac{Z - (c+r)^{b(1-\alpha)}}{2Z} \tag{10.20}$$

Equation (10.20) is obtained by using $P_{\text{peak}} = P_{\text{off-peak}}$ in the cost recovery constraint (10.3), leading to a price of $c+r$, and using that price in equation (10.14). All of the theoretical results and other related ones are studied in more details in Pineau and Schott (2004). In particular, conditions under which average cost pricing leads to a *lower* capacity K than TOU pricing are identified.

3. Numerical analysis: Pricing and technology options explored

This section analyzes different pricing and technology scenarios and their impact on capacity requirements and emissions for residential and business consumers in Ontario. The numerical analysis aims to provide some policy advice in terms of pricing and technology choices, in order to limit future capacity requirements and GHG emissions in Ontario.First we define the different scenarios we will explore, then we present the set of parameters used for the analysis. Numerical results are presented and analyzed in the last subsection.

3.1 Scenarios

We analyze different scenarios with respect to technologies used, changes in pricing schemes, elasticities of demand and transfer of demand, and the use of CO_2, SO_2 and NO_x emission pricing (also called "emission costs" and "allowance price").

Technologies Although ECSTF (2004) only considered nuclear and natural gas (combined-cycle gas turbine, or CCGT) power plants as the two principal options for Ontario's power generation, coal generation stations are still an option considered by some, despite the provincial plan to phase out all coal power plants by the end of 2007. Indeed, the Canadian Energy Research Institute (CERI)-sponsored study Ayres, MacRae and Stogran (2004) maintains scrubbed coal as a possible major source of power for Ontario. We, therefore, consider coal, natural gas and nuclear power as three mutually exclusive options for power generation in Ontario. Additional hydropower capacity, other renewable energy options and imports, all being heavily constrained, are excluded from the analysis.[4]

Pricing scheme and elasticities We consider TOU pricing as an alternative to the current two-step flat rate pricing scheme for small businesses and residents in Ontario. For instance, ECSTF (2004) recommends the introduction of TOU tariffs to favour conservation.This is our main motivation to study TOU pricing with and without the transfer of demand. In the long run, retail consumer demand will become more price and cross-price elastic, resulting in increased transfer of demand from the peak to the off-peak period. The impacts on capacity requirements, energy consumption, equilibrium prices and emissions are studied here.

Figure 10.2 shows the hourly variation of capacity requirements in Ontario (2003 average) and how two different time of use periods can

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[4] In the analysis of GHG emissions, an adjustment is made for the fixed amount of electricity from hydropower available in Ontario.

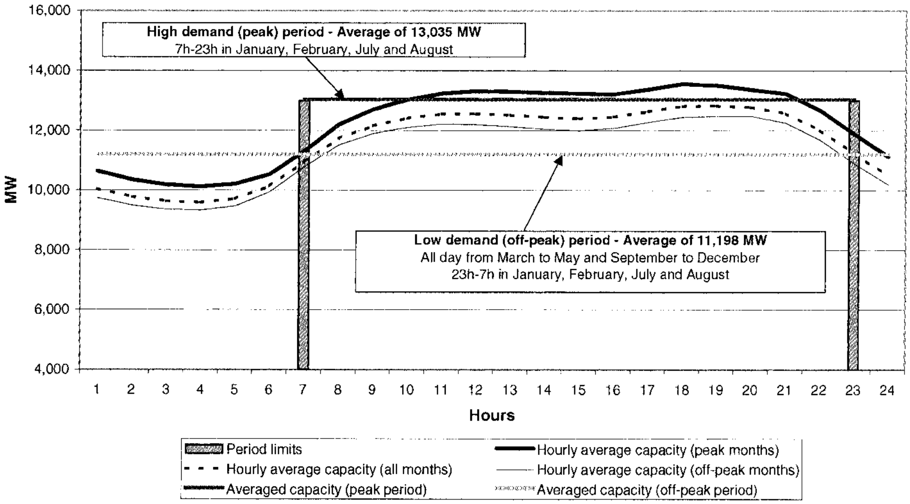

Figure 10.2. Average Hourly Ontario Energy Demand in 2003

be defined. See Table 10.2 for more on the definition of the two time periods used in Figure 10.2.

GHG emission costs The main GHGs involved in electricity production are CO_2 and NO_x. We include a third key air pollutant in the analysis, SO_2, because of its environmental impact in coal-fired power plants (see Ontario Ministry of the Environment, 2001). New costs will be associated with the emission of these gases, which is analyzed here.

3.2 Data

As industrial consumers already have electricity tariffs that vary by time of use, we focus our analysis on the residential and commercial sectors, where consumers are still billed according to a flat rate structure. Tables 10.2, 10.3 and 10.4 present the parameters' value we use for the analysis. The main source for the values is Royal Academy of Engineering (2004).Comparable values can be found in Ayres, MacRae and Stogran (2004).

Table 10.3 presents the emission rates of CO_2, SO_2, NO_x for different technologies. Average data of CO_2 emission for different fuels are also available in EPA (2000).

Table 10.2. Parameters for simulating Ontario's electricity sector

Value	**Explanation** All prices and costs are in Canadian dollars (Can$1 = US$0.75 = Euro 0.61; July 6, 2004 exchange rates)
Coal	
$c = \$21.98 + \$37 = \$58.98/\text{MWh}$	The first value ($21.98) comes from (Royal Academy of Engineering, 2004, p. 28), estimate for coal power production costs (excluding capital cost and carbon emissions), using a currency exchange rate of £1 = Can$ 2.42. It has, however, been adjusted to reflect the much lower cost of coal in Canada (we used the CERI coal price of $1.90/GJ; the UK value was £1.39/GJ or $3.36/GJ). The second value ($37) is the sum of other variable charges paid by final consumers in Ontario: *Transmission, Wholesale Market Service, Debt Retirement and Distribution* charges (see for instance Hydro Ottawa, 2004).
$r = \$24.08/\text{MW}$	Also based on Royal Academy of Engineering (2004) estimations, this value is the hourly value of a MW of capacity, amortized over 30 years with a yearly discount rate of 10%. The estimated purchase price is $1,988,842/MW.
$\text{GHG} = \$16.54/\text{MWh}$	This is the cost of CO_2, SO_2 and NO_x emissions based on emission rates for coal (Table 10.3) and emission costs (Table 10.4).
Nuclear	
$c = \$22.80 + \$37 = \$59.80/\text{MWh}$	The first value ($22.80) comes from (Royal Academy of Engineering, 2004, p. 45),estimate for nuclear power production costs (excluding capital cost), using a currency exchange rate of £1 = Can$ 2.42. The second value ($37) is the sum of other variable charges paid by final consumers in Ontario.
$r = \$31.56/\text{MW}$	Also based on Royal Academy of Engineering (2004) estimations, this value is the hourly value of a MW of capacity, amortized over 40 years with a yearly discount rate of 10%. The estimated purchase price is $2,703,770/MW and includes the cost of decommissioning.
$\text{GHG} = \$0.0044/\text{MWh}$	This is the cost of CO_2, SO_2 and NO_x emissions based on emission rates for nuclear technology (Table 10.3) and the emission costs (Table 10.4).
Natural Gas	
$c = \$44.62 + \$37 = \$81.62/\text{MWh}$	These values also come from Royal Academy of Engineering (2004), page 40,for combined-cycle gas turbine (CCGT) power production cost and from Hydro Ottawa (2004).

Table 10.2 (continued)

$r = \$9.15/\text{MW}$ $\text{GHG} = \$5.27/\text{MWh}$	Also based on Royal Academy of Engineering (2004) estimations, this value is the hourly value of a MW of capacity, amortized over 25 years with a yearly discount rate of 10%. The estimated purchase price is \$727,470/MW. This is the cost of CO_2, SO_2 and NO_x emissions based on emission rates for new CCGT (Table 10.3) and the emission costs (Table 10.4).
$b = -1.29$ $\alpha = 0.667$	Mountain and Lawson (1995) have studied the reaction of Ontarian consumers to TOU prices in an experiment. Based on their results, we estimated the peak period elasticity at 0.86 (peak period being 7 a.m. to 11 p.m. in January, February, July and August). Also based on their results, the off-peak period elasticity was set at 1.29. This means that during peak periods, the electricity consumption is inelastic, whereas it is elastic during the off-peak period. With these two elasticity parameters, it is straightforward to find the value of the parameter $\alpha = 0.667$. See Stevens and Lerner (1996) for a similar range of long-run elasticities.
$Z = 0.176865$ $a = 3{,}192{,}468$	These two parameters are scaled from Ontario's 2003 hourly electricity consumption (the data comes from IMO (2004b). See Figure 10.2 for more details on the consumption data. In 2003, the average (weighted) wholesale electricity price was \$57/MWh, but the final non-industrial consumers only paid a "capped" price of \$43/MWh (the Ontarian government subsidized the difference). During the high demand (peak) period (7 a.m. to 11 p.m. in January, February, July and August) the average hourly demand was 13,035 MW. During the low demand period (11 p.m. to 7 a.m. of the four months and 24h a day for the other eight months), the average hourly demand was 11,198 MW. These numbers are the hourly weighted average for residential and commercial consumers (67% of the demand, see Table 10.1). Using these numbers, the elasticity value b and α given above and demand equations (10.7) and (10.8), it is straightforward to obtain Z and a.
$\omega = 0.22$	From the definition of peak and off peak periods, we have 1,936 hours of high demand and 6,824 hours of low demand in a year (total of 8,760). This gives ω.

Table 10.3. Emission rates by technology (t/GWh)

	Coal	Natural Gas	Natural Gas New CCGT	Nuclear
CO_2	964.52	528.60	349.27	0.23
SO_2	3.91	0.82	0.01	0.000286
NO_x	1.10	0.67	0.026	0.000859
Sources:	*OPG (2003:42)* *Nanticoke Station, 2002*	*OPG (2003:42)* *Lennox Station, 2002*	*Chen et al. (2003)*	*OPG (2003:44)* *All nuclear stations, 2002*

Table 10.4. Allowance price of emission ($/t)

	1999 US$ 2005 projection	2004 Can$	Can$ Value used
CO_2	40 - 50	15	15
SO_2	200 - 300	-	250
NO_x	1,000 - 1,100	-	1,000
Sources:	*EIA (2001:24)*	*Ayres et al. (2004:18)*	

3.3 Scenario analysis

Firm-peak or shifting-peak? Using Ontario's parameter value in condition A (equation (10.16)) and equation (10.20), we obtain the results in Table 10.5. Condition A is never satisfied under the current costs and demand conditions, so a shifting-peak is obtained in all cases. This means that the full capacity would be used all the time with TOU pricing, while prices would differ. If TOU pricing was used and consumers transferred some demand from the peak to the off-peak period, if would take a transfer close to 10% before prices would be equal in both periods (at the level $c + r$).The exact value of γ at which this happens, in each case, is indicated in the last column of Table 10.5.

Under the set of parameters presented in this section, we derive numerical results for all the scenarios defined previously. Solutions to nonlinear equations (10.5), (10.11) and (10.15) have been obtained with MS Excel's solver. Results are now presented and discussed.

Comparing technologies under average cost pricing with no emission cost In 2003, Ontario residential and commercial consumers were billed according to a subsidized flat rate (second column of Table 10.6). If a cost recovery average cost price were introduced for a

Table 10.5. Predicted market conditions with parameters' value

	GHG cost/MWh	c	r		Condition A RHS	γ for which $P_{\text{peak}} = P_{\text{off-peak}}$
Coal		58.98	24.08	$>$	0.32	7.74%
with GHG allowance price	16.5453	75.53	24.08	$>$	2.66	10.91%
Nuclear		59.80	31.56	$>$	0.42	9.43%
with GHG allowance price	0.00438	58.80	31.56	$>$	0.42	9.43%
Natural Gas		81.62	9.15	$>$	3.70	9.32%
with GHG allowance price	5.26755	86.89	9.15	$>$	4.68	10.29%

Table 10.6. Average cost pricing (ACP)

	2003 Ontario situation	Coal	Nuclear	New CCGT
$Q_{\text{off-peak}}$ (MW)	11,198.00	10,087.17	8,666.67	9,300.69
Q_{peak} (MW)	13,035.00	12,158.04	10,988.01	11,517.57
$P_{\text{off-peak}}$ (\$)	80.00	86.75	97.58	92.38
P_{peak} (\$)	80.00	86.75	97.58	92.38
MWh off-peak	76,415,152.00	68,834,877.31	59,141,359.24	63,467,917.06
MWh peak	25,235,760.00	23,537,974.94	21,272,780.98	22,298,016.44
Total MWh	101,650,912.00	92,372,852.25	80,414,140.22	85,765,933.49
Non-hydro MWh	87,419,784.32	70,372,852.25	58,414,140.22	63,765,933.49
CO_2 emissions (t)	34,918,064.12	67,876,023.45	13,435.25	22,271,527.59
SO_2 emissions (t)	110,597.66	275,157.85	16.71	637.66
NO_x emissions (t)	41,417.01	77,410.14	50.18	1,657.91

single technology (either coal, nuclear technology or new CCGT), the price would increase in any case, leading to a lower peak demand. Capacity requirement would therefore be reduced, as well as the different GHG emissions. Details of these results are presented in Table 10.6.

In terms of emissions, however, the use of coal would lead to an additional 33 Mt compared to 2003 data, while the exclusive use of nuclear power would eliminate almost 34 Mt of CO_2 emitted in 2003 by residential and commercial consumers through their electricity consumption. This would represent a 17% decrease from the 2001 Ontario emission level and exceed the Kyoto target. If the full capacity was replaced by new CCGT, emission could be reduced by almost 13 Mt.

Table 10.7. TOU Pricing (no transfer of demand)

	2003 Ontario situation	Coal	Nuclear	New CCGT
$Q_{\text{off-peak}}$ (MW)	11,198.00	11,252.33	10,091.60	10,166.95
Q_{peak} (MW)	13,035.00	11,252.33	10,091.60	10,166.95
$P_{\text{off-peak}}$ (\$)	80.00	79.70	86.72	86.22
P_{peak} (\$)	80.00	94.92	107.73	106.80
MWh off-peak	76,415,152.00	76,785,923.50	68,865,101.93	69,379,274.72
MWh peak	25,235,760.00	21,784,517.57	19,537,344.27	19,683,217.45
Total MWh	101,650,912.00	98,570,441.07	88,402,446.20	89,062,492.16
Non-hydro MWh	87,419,784.32	76,570,441.07	66,402,446.20	67,062,492.16
CO_2 emissions (t)	34,918,064.12	73,853,721.83	15,272.56	23,422,916.64
SO_2 emissions (t)	110,597.66	299,390.42	18.99	670.62
NO_x emissions (t)	41,417.01	84,227.49	57.04	1,743.62

This analysis of capacity requirements and emissions under different technology choices clearly illustrates the important differences involved with each technology.

Comparing technologies under TOU pricing (without demand transfer) If instead of average cost pricing a TOU pricing scheme was introduced, important further capacity reductions would be observed. 3,000 MW of capacity could be "saved" from the 2003 data. However, price increases would be large during peak periods (especially with nuclear technology and new CCGT). They would, however, be limited during off-peak periods, especially under the coal option, where a small price decrease would even occur. With the off-peak period being the price-elastic period, consumption would be much more important during this period than under average cost pricing. This explains the net increase in emissions, compared to average cost pricing, despite the lower consumption in the peak period.

Comparing technologies under TOU pricing with demand transfer Table 10.8 presents data for the situation where the TOU price difference leads to a transfer of demand such that there is no more price difference between peak and off-peak. The required transfer proportion is indicated in brackets for each case.

Under this scenario, consumers would have taken full advantage of the price differential between the peak and off-peak periods. This would lead to a similar price in both periods. Capacity reductions are lower

Table 10.8. TOU pricing with transfer of demand (price equalization case)

γ	2003 Ontario situation	Coal 7.74%	Nuclear 9.43%	New CCGT 9.32%
$Q_{\text{off-peak}}$ (MW)	11,198.00	11,644.23	10,531.50	10,604.00
Q_{peak} (MW)	13,035.00	11,644.23	10,531.50	10,604.00
$P_{\text{off-peak}}$ ($)	80.00	83.06	91.36	90.77
P_{peak} ($)	80.00	83.06	91.36	90.77
MWh off-peak	76,415,152.00	79,460,240.94	71,866,924.49	72,361,683.32
MWh peak	25,235,760.00	22,543,233.65	20,388,975.06	20,529,340.40
Total MWh	101,650,912.00	102,003,474.59	92,255,899.54	92,891,023.72
Non-hydro MWh	87,419,784.32	80,003,474.59	70,255,899.54	70,891,023.72
CO_2 emissions (t)	34,918,064.12	77,164,951.31	16,158.86	24,760,107.86
SO_2 emissions (t)	110,597.66	312,813.59	20.09	708.91
NO_x emissions (t)	41,417.01	88,003.82	60.35	1,843.17

than under TOU pricing with no transfer, as Table 10.8 shows. However, significant reductions in capacity requirements would still be obtained, with much smaller price increases than without considering transfer of demand.

This scenario illustrates particularly well the importance of "educating" consumers: the combined effect of elastic demand and transfer of demand (from the peak to the off-peak periods) has the power to reduce consumption while limiting price increase. Emissions, however, are not reduced as much as with average cost pricing.

Comparing pricing schemes To better illustrate how a move towards full cost recovery average cost prices could have an impact on capacity and emissions, Table 10.9 shows (in percentage terms) how the variables change under the three technology options with average cost pricing. The biggest reduction in capacity is observed with nuclear power, because of the biggest price increase. Coal almost represents a status quo in terms of price and capacity, but it is the only technology leading to an increase in emission, almost +100% for CO_2 from the 2003 data. Nuclear technology would eliminate almost all GHG emissions, and natural gas, with new CCGT, would reduce CO_2 emission by more than a third.

Table 10.10 shows how TOU pricing, with and without transfer of demand, would influence capacity, prices and emissions compared to average cost pricing.

What is remarkable is the capacity reduction TOU pricing would bring: between 7.45% and 11.73% (depending on the technology used) compared to average cost pricing with full cost recovery (see Table10.10). However, if transfer was taking place and reaching its maximum, the ca-

Table 10.9. From the 2003 situation to full cost recovery average cost (% change)

	2003 Ontario situation	Coal	Nuclear	New CCGT
$Q_{\text{off-peak}}$ (MW)	11,198.00	−9.92%	−22.61%	−16.94%
Capacity Q_{peak} (MW)	13,035.00	−6.73%	−15.70%	−11.64%
$P_{\text{off-peak}}$ ($)	80.00	8.44%	21.97%	15.48%
P_{peak} ($)	80.00	8.44%	21.97%	15.48%
Energy off-peak (MWh)	76,415,152.00	−9.92%	−22.61%	−16.94%
Energy peak (MWh)	25,235,760.00	−6.73%	−15.70%	−11.64%
Total Energy (MWh)	101,650,912.00	−9.13%	−20.89%	−15.63%
Non-hydro energy (MWh)	87,419,784.32	−19.50%	−33.18%	−27.06%
CO_2 emissions (t)	34,918,064.12	94.39%	−99.96%	−36.22%
SO_2 emissions (t)	110,597.66	148.79%	−99.98%	−99.42%
NO_x emissions (t)	41,417.01	86.90%	−99.88%	−96.00%

Table 10.10. From average cost to TOU pricing, with and without transfer (% change)

	Coal		Nuclear		New CCGT	
	TOU	TOU/ Transfer	TOU	TOU/ Transfer	TOU	TOU/ Transfer
Capacity Q_{peak}	−7.45%	−4.23%	−8.16%	−4.15%	−11.73%	−7.93%
$P_{\text{off-peak}}$	−8.12%	−4.25%	−11.13%	−6.37%	−6.67%	−1.75%
P_{peak}	9.42%	−4.25%	10.40%	−6.37%	15.61%	−1.75%
Energy off-peak	11.55%	15.44%	16.44%	21.52%	9.31%	14.01%
Energy peak	−7.45%	−4.23%	−8.16%	−4.15%	−11.73%	−7.93%
Total Energy	6.71%	10.43%	9.93%	14.73%	3.84%	8.31%
Emission change	8.81%	13.69%	13.68%	20.27%	5.17%	11.17%

pacity reduction would be limited to 4% to 8%. In terms of emissions, however, important increases would be observed compared to average cost pricing. This would not be an issue with nuclear technology (emitting almost no GHG), but would be with the two other possible options.

Comparing elasticities All previous results have been obtained with price elasticities of −1.29 and −0.86 for the off-peak and peak demand periods, respectively. These are the long-run residential elasticities discussed in the literature (see the discussion and reference in Table 10.2). However, if electricity demand remained price inelastic (at a level of −0.5 in both periods, for example), the results presented in Table 10.11

would be obtained. Results are presented as percentage changes from the similar situation with the initial elasticities.

The lesson to be drawn from Table 10.11 is that if residential and commercial electricity demand remains inelastic in the long run, both capacity and emissions would increase, making it challenging to reduce emissions and to limit capacity expansion. This makes it even more important to create incentives and educate consumers so that they become more responsive to TOU price differences.

Comparing solutions with and without GHG allowance price Some source of optimism can, however, be found in the introduction of a GHG allowance price. Indeed, when adding such a price to GHG emissions (following Tables 10.3 and 10.4), the production cost changes, and this significantly affects the results as Table 10.12 shows. Table 10.12 presents the percentage change in capacity requirements, prices and emissions under different pricing schemes and with GHG allowance prices.

Coal as the major technology with emission pricing would result in the largest capacity reductions, but at significant costs for consumers and the environment. New CCGT fares second best in terms of capacity reduction and energy reduction. Nuclear technology has the advantage of the least price increases and the lowest emissions. An interesting observation is that, under average cost pricing both nuclear technology and new CCGT result in the same price, although capacity and energy consumption changes. The introduction of TOU pricing, with transfer of demand, seems to be particularly interesting under the nuclear technology option since it will lead to a lower price and smaller capacity requirements than under average cost pricing. For new CCGT, on the other hand, TOU pricing leads to almost identical price increases to average cost pricing, but to larger energy consumption and emissions.Since average cost pricing most closely represents the status quo, it would also be politically the more feasible solution for new CCGT.

3.4 Results limitations

A few elements have to be taken into account when analyzing these results.

Natural gas price uncertainty. This element is not included in the analysis, but could prove to be a major issue if CCGT plants were built. The uncertainty element certainly deserves more consideration because the world fossil fuel market is predicted to be rather tight and volatile in the future.

Table 10.11. Difference between period-specific price elasticities and identical inelastic demand in both periods (% change from period-specific price elasticity)

	Coal			Nuclear			New CCGT		
	Av. Cost	TOU	TOU/ Transfer	Av. Cost	TOU	TOU/ Transfer	Av. Cost	TOU	TOU/ Transfer
Capacity Q_{peak}	3.38%	1.42%	2.12%	8.72%	7.83%	7.66%	5.60%	7.38%	7.27%
$P_{\text{off-peak}}$	−0.82%	−3.36%	0.00%	−2.38%	−2.31%	0.00%	−0.53%	−2.38%	0.00%
P_{peak}	−0.82%	9.95%	0.00%	−2.38%	6.55%	0.00%	−0.53%	6.78%	0.00%
Energy off-peak	7.05%	1.42%	2.12%	18.41%	7.83%	7.66%	12.34%	7.38%	7.27%
Energy peak	3.38%	1.42%	2.12%	8.72%	7.83%	7.66%	5.60%	7.38%	7.27%
Total Energy	6.12%	1.42%	2.12%	15.85%	7.83%	7.66%	10.58%	7.38%	7.27%
Emission change	8.03%	1.83%	2.70%	21.81%	10.43%	10.06%	14.24%	9.80%	9.53%

Table 10.12. Percent change from Status Quo (Ontario 2003 situation) with allowance price of emissions, under different technologies and pricing

	2003 Ontario Situation	Coal			Nuclear			New CCGT		
		Av. Cost	TOU	TOU/ Transfer	Av. Cost	TOU	TOU/ Transfer	Av. Cost	TOU	TOU/ Transfer
Capacity Q_{peak}	13,035.00	−20.87%	−29.84%	−26.22%	−15.71%	−22.58%	−19.21%	−15.90%	−26.86%	−23.34%
$P_{\text{off-peak}}$	80.00	31.29%	17.00%	24.51%	21.98%	8.40%	14.21%	22.31%	13.29%	20.05%
P_{peak}	80.00	31.29%	51.00%	24.51%	21.98%	34.67%	14.21%	22.31%	43.87%	20.05%
Total Energy	101,650,912.00	−27.44%	−21.19%	−17.12%	−20.90%	−13.04%	−9.25%	−21.15%	−17.84%	−13.88%
CO_2 emissions	34,918,064.12	42.96%	60.52%	71.94%	−99.96%	−99.96%	−99.95%	−41.83%	−38.47%	−34.44%
SO_2 emissions	110,597.66	82.97%	105.45%	120.07%	−99.98%	−99.98%	−99.98%	−99.47%	−99.44%	−99.41%
NO_x emissions	41,417.01	37.46%	54.34%	65.33%	−99.88%	−99.86%	−99.85%	−96.35%	−96.14%	−95.89%

Nuclear risks. Although the decommissioning cost of nuclear power is taken into account in the capacity cost estimates used (see Table 10.2), it is difficult to assign a dollar value to nuclear risks and the uncertain effects of nuclear waste. There are also political costs associated with nuclear waste because citizens react strongly to nuclear waste management issues. Furthermore, with the many technical and financial problems Ontario nuclear power production faced in the past, improvements — both at the technology and management levels — are required before a nuclear option becomes realistic in Ontario.

Single technology model. The model developed only accounts for a single technology, which is not always the case in electricity markets. Some marginal changes would occur with the inclusion of more technologies, which could alter some of the results. We believe, however, that these changes would not invalidate the main elements of the analysis. Furthermore, the discussion in Ontario at present is focussed on investing into one major base-load technology besides hydropower (either nuclear power, natural gas, or even maybe "cleaner" coal if some major policy shifts were to occur). Our analysis has also shown that consumption in peak and off-peak periods could be identical (a shifting-peak occurs) once prices are allowed to vary between periods. Our model is simple but demonstrates that the gap between peak and off-peak consumption can be considerably closed.

4. Conclusion

We have introduced an electricity market model to analyze technology and pricing choices and applied it to the Canadian province of Ontario. The electricity sector of this province faces important constraints: it has to invest in new capacity and reduce its GHG emissions. Achieving both of these objectives is attainable, as our analysis shows, if nuclear power or new CCGT are chosen, especially with TOU pricing. However, important efforts would be needed to ensure that residential and commercial consumers become price-elastic in the long run. Indeed, if demand remained price-inelastic, much smaller gains would be observed. The use of GHG allowance prices, by increasing prices, has a beneficial effect on both emissions and capacity requirements. Price levels, however, would suffer from new GHG-related costs, and this might prove to be a difficult policy road to follow, unless consumers transfer demand between periods.

The originality of our analysis resides in the use of a model that allows a transfer of demand, as TOU pricing creates an incentive to reduce demand during peak periods, to increase demand during off-peak, and to shift demand from one period to the other. We illustrate the complexity of electricity options, by showing how various goals can be contradictory (emission and capacity reduction) and sensitive to both technology and pricing choices. We nevertheless provide some optimistic results, especially if consumers are given the appropriate tools to react to price incentives.If Ontario decides to replace the current coal capacity with nuclear technology, it would be highly recommendable to introduce TOU pricing.If instead Ontario decides on new CCGT, a switch to TOU pricing might not be worthwhile and actually detrimental to emission target objectives. Despite its low cost (before emissions are accounted for) coal does not seem to be a viable option unless it could become significantly cleaner.

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Chapter 11

IMPLICATIONS OF THE INTEGRATION OF ENVIRONMENTAL DAMAGE IN ENERGY/ENVIRONMENTAL POLICY EVALUATION: AN ANALYSIS WITH THE ENERGY OPTIMISATION MODEL MARKAL/TIMES

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Abstract The objective of this paper is to describe an approach to integrate the possible interactions between environmental targets in an energy system optimisation model, MARKAL/TIMES, so as to allow for an integrated policy evaluation. The environmental problems considered in this study are global warming and local air pollution, both linked to energy production and consumption and their abatement possibilities are interrelated. This explains the choice of a partial equilibrium model for the energy market to study these policy questions. With the damage generated by emissions integrated in its objective function, the model allows to optimally compute trade-offs between environment protection and economic costs. In this paper, the problem is examined from the viewpoint of a national policy maker having to address global warming and local air pollution. The MARKAL/TIMES model and the integration of the externalities are described. The data used for the quantification and the valuation of the externalities linked to the supply and use of energy rely heavily on the ExternE EU project dedicated to the evaluation of the external cost of energy. An application with the Belgian MARKAL/TIMES model is presented.

1. Introduction

Integrating sustainable development in the energy system evolution has become a major concern in the definition of energy policies. Moreover, countries are signing agreements imposing abatement of multiple emissions that are related in some way or other. For instance, Europe has signed the Kyoto protocol aiming at GHG emission reduction and the Gothenburg protocol aiming at local air pollution abatement; both targets are closely linked to the energy system and its emissions. Therefore it seems important to integrate in the policy design the interactions between different environmental policies because of their possible impact on the cost, the benefit and the efficiency of the policies. However most emission reduction strategies still focus on only one pollutant.

The objective of this paper is to describe an approach to integrate the possible interactions between environmental targets in an energy system optimisation model, MARKAL/TIMES, so as to allow for an integrated policy evaluation. The environmental problems considered in this study are global warming and local air pollution; they are both linked to energy consumption and their abatement possibilities are interrelated. This explains the choice of a partial equilibrium model for the energy market to study these policy questions. With the damage generated by emissions integrated in its objective function, the model allows to evaluate the full costs and benefits, i.e., the direct cost and the externalities, of energy policies and of energy systems by balancing the trade-offs between global and local environment protection and economic costs. This goes further than a simple ex-post computation of the implications of a strategy for one pollutant on the emission of another pollutant.

In the first section, the problem is examined in a formal framework considering a national policy maker having to address global warming and local air pollution. Then, in the second section, a brief description of the MARKAL/TIMES model and of the integration of the externalities in the model is given. The data used for the quantification and the valuation of the externalities linked to the supply and use of energy rely heavily on the ExternE EU project dedicated to the evaluation of the external cost of energy. Finally in the last section, an application with the Belgian MARKAL/TIMES model is presented.

2. The formal framework

For illustration purposes, we consider the market for only one energy service (home heating, car kilometres, etc.). This demand q can be satisfied by an energy production function $Q(E, I)$ that uses two inputs: primary energy E and other inputs I (insulation, more efficient engines, etc.). The production of energy services generates two pollutants. The first is say CO_2, which can only be abated through a reduction in energy consumption and the second is say SO_2, for which specific abatement efforts can be made[1]. The specific abatement efforts are denoted sr_s and they represent the emission reduction efforts per unit of energy. The benefits of energy use are measured via the gross consumer surplus $C(q)$, the area under the inverse demand function. The costs of energy use are given by the constant marginal costs for energy and other inputs, by the abatement cost function per unit of energy use $c_s(\mathrm{sr}_s)$, which is convex and by the damages from pollution (constant marginal damages p_{dc} and p_{ds}). The damage from pollution is assumed not to interfere with the demands for energy services.

Assuming that there are no other market distortions in the economy and that the policy maker is only interested in the benefits and costs directly linked to his policy[2], the best he can achieve is to choose the level of E, I and sr_s such that the difference between gross consumer surplus and costs of inputs and environmental damage is maximised given the production possibilities.

$$\max_{q,I,E,sr_s} C(q) - p_I I - p_e E - c_s(\mathrm{sr}_s)E - p_{\mathrm{ds}}\mathrm{es}(1 - \mathrm{sr}_s)E - p_{\mathrm{dc}}\mathrm{ec}E \quad (11.1)$$

under the production constraint

$$Q(E, I) \geq q(p), \quad (11.2)$$

where

$q(p)$: demand for an energy service

$C(q)$: the gross consumer/producer surplus (surface under the demand curve)

p_I, p_e: the price of capital and energy

p: the price of the energy service (shadow price of the constraint)

$Q(E, I)$: the production function

I, E: the production inputs, annualised capital and energy

$c_s(\mathrm{sr}_s)$: cost, per unit of energy, of SO2 emission abatement per reduction sr_s

p_{ds}, p_{dc}: damage from SO_2 and CO_2 emissions, assumed constant here[3]

es, ec: emission coefficients of SO2 and CO2 per energy unit

At the optimum and assuming an internal solution, the first best policy is characterised by three first order conditions:

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[1] The SO_2 abatement technologies are assumed not to modify directly energy consumption and hence CO_2 emissions.

[2] This is obviously a strong assumption as income distribution issues (within generations and over generations) are ruled out.

[3] If a constraint is imposed on CO_2 instead of a damage per unit of CO_2 emission, the shadow price of this constraint would replace the damage figure in the computation.

- The marginal benefit (in terms of energy services) of other inputs I, has to equal its cost. If energy and other inputs are substitutes, this condition shows that when energy inputs are more expensive, other inputs will be used more.

$$\frac{\partial Q}{\partial I} = p_I \tag{11.3}$$

- The marginal benefit (in terms of energy services) of energy inputs E, has to equal its full cost. The full cost consists of the resource cost of energy, the costs of air pollution abatement, the associated remaining local air pollution damage and the damage from CO_2:

$$p\frac{\partial Q}{\partial E} = p_e + c_s + p_{\mathrm{ds}}\mathrm{es}(1 - \mathrm{sr}_s) + p_{\mathrm{dc}}. \tag{11.4}$$

or, in terms of tonne CO_2 abated,[4] the marginal abatement cost is equal to the damage from SO_2 and CO_2 taking into account the SO_2 abatement

$$p\frac{\partial Q}{\mathrm{ec}\partial E} - \frac{p_E}{\mathrm{ec}} = c_s + \frac{p_{\mathrm{ds}}\mathrm{es}}{\mathrm{eec}(1 - \mathrm{sr}_s)} + p_{\mathrm{dc}}. \tag{11.5}$$

Because of the interaction between SO_2 and CO_2 reduction (through energy consumption), the optimum abatement effort for CO_2 takes into account both the damages from CO_2 and from SO_2. It will therefore be higher than when there is no interaction. It has also implications for the choice of policy instrument: the policy instrument has to give the incentive to internalise this interaction.

- The condition for the optimal abatement of local air pollution, i.e., the cost of increasing the fraction of local pollution abated should equal the damage saved:

$$\frac{\partial c_{\mathrm{cs}}}{\partial \mathrm{sr}_s} = p_{\mathrm{ds}}\mathrm{es}. \tag{11.6}$$

In our formulation, where the marginal damage of local air pollution is assumed constant and where the abatement process itself does not require any energy services, the optimal level of local air pollutants abatement per unit of energy is independent of the CO_2 emission damage.

If only local pollution objectives are pursued and the damage from CO_2 is not taken into account, only condition (11.6) holds. Obviously there will always be an impact on energy use and CO_2 emissions in our illustrative model because condition (11.4) that governs energy input use will take into account the marginal SO_2 abatement cost and the remaining damage. The impact of local air pollution policies on the total

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[4] Improving energy efficiency is the option to abate CO_2 emissions.

CO_2 emissions will only be important if the SO_2 abatement policies are very costly or offer small abatement possibilities so that the remaining local air pollution damage is large.

When only GHG damage are taken into account, the associated local air pollution savings may be important if there were no local air pollution policy in place or if it were very costly. Indeed, in that case the reduction efforts for local air pollution (sr_s) will be small or zero and the air pollution damage of every unit of energy used will be large so that energy saving produces large reduction in local pollution.

When both targets are taken into account, in the condition that governs the use of energy (11.5) the cost of energy is increased with the cost of the remaining local air pollution at its optimal level as specified in (11.6).

This framework can be extended to cover more complex local air pollution damage functions and substitution between energy sources. Our simple analytical framework conveys a few insights that will be useful to understand the numerical results of the later section:

1. Local air pollution benefits can reduce the cost of GHG policies, especially when air pollution policies are not optimised or their abatement are very costly.
2. When an optimal local air pollution is in place, the total cost and the marginal cost of a GHG policy are larger than without an optimal local air pollution policy as the benefits in terms of local pollution are smaller.

3. Integration in the MARKAL/TIMES framework

3.1 The modeling principle

MARKAL/TIMES[5] is a partial equilibrium model representing all energy demand and supply activities and technologies with a horizon of up to 40/50 years, with their associated emissions (e.g., CO_2, SO_2, NOx, VOC and PM). It covers all activities from import of energy, transformation into secondary energy, transport and distribution up to and including the transformation of final energy (at the consumers' end) into energy services. The different types of energy services include all energy

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[5] The Markal model has been implemented in Belgium with support of the Federal Science Office by CES-KULeuven and VITO since 1990. The current use is covered by the "Global Change and Sustainable Development" research program of the Science Policy Office, contract no. GC/DD/221 and 222". The model structure is the product of a 20 year cooperation in ETSAP, which is an implementing agreement of the IEA, and the model is used in more than 25 countries for energy policy analysis.

services ranging from delivery of process heat to some industrial sectors up to home heating and electricity demand for household appliances. This demand for energy services is satisfied by investing and operating technologies of demand (heating equipment, energy saving, etc.) and supply (power plants, etc).

The basic idea of the model is to compute a competitive energy market equilibrium by maximising over the model horizon the discounted sum of consumer and producer surpluses including possibly the environmental benefits subject to technological feasibility constraints, to constraints on available production capacity and to policy constraints. The policy constraints can be overall emission constraints (e.g., Kyoto), a ban on certain technologies (e.g., nuclear), existing taxes etc.. The costs in the different periods are weighted using a discount factor. The use of a 5% discount rate can be justified to reflect a "social" time preference rate and to analyse the optimal decisions for society as a whole. In scenarios which should reflect more the behaviour of the consumers and producers as individual private agents, a 10% discount rate is more appropriate, corresponding approximately to an average payback period of 7 years. Perfect foresight is assumed for all economic agents.

Representing the energy system as a network of processes and commodities connected by commodity flows, this framework allows to study the competition and interaction between different elements of the system (e.g., between fuel switching and the use of more efficient technologies to reduce carbon emissions). The methodology focuses on the time development of the energy system and its technology portfolio and the economic implications, at a region, country or group of countries level, taking into account the trade-off possibilities.

This modelling principle allows us to sketch what can be the best response and economic cost of certain energy and environment policies.

This ambitious and global approach has a cost in terms of a simplified representation of energy users and producers in the model. It is assumed that there is perfect coordination between demand and supply on the basis of social marginal costs. This implies that there are no transaction costs and that all agents share the same subjective beliefs, that they are rational and finally that they use "prices" equal to the discounted marginal costs corrected for imputed shadow prices when emission or technological constraints are imposed.

3.2 Demand for energy services

The model distinguishes two demand concepts, the demand for energy services (demand for heated homes, passenger kilometres, industrial process heat, etc.) and the final energy demand. The final energy demand corresponds to the delivery of energy products (oil products, gas, coal, and electricity) to the consumers (non-energy producing firms, households). It is one of the inputs into the production of energy services. The model is driven by the demand functions for energy services. These demand functions give the level of energy services demanded as a function of their cost. E.g., in the case of home heating the cost of heating the house corresponds to the cost of investment in heating appliances and home insulation plus the price of gasoil corrected by an energy conversion efficiency that is itself a function of these investments. Movements along the demand curve for energy services correspond to non specified substitution outside the energy system, with other inputs (capital, labour and materials) or other products in the industrial sector or with other goods (or comfort) for the consumers. The price elasticities of the demand for energy services are derived from the literature. As most of the studies concern the price elasticity of final energy demand and not of energy services, a correction has been applied to take into account that some of the substitution possibilities (e.g., by investing in energy saving or more efficient equipment) are modelled within MARKAL/TIMES. The position of the demand curves for energy services is determined by exogenous factors, such as the level of income or of equipment (electric appliances, number of houses, cars, etc.) for households or the level of industrial activity for firms. These exogenous parameters depend on the macroeconomic assumptions underlying a study.

For the Belgian model, the price elasticities for the industrial sectors are derived from a study on the estimation of production functions for the industrial sectors in Belgium. They give a price elasticity of final energy demand varying from −0.4 to −0.8. A figure of −0.35 has been chosen for all industrial sectors, correcting for the substitution possibilities within MARKAL/TIMES. For the households and the transport sector, an average price elasticity of −0.3 was chosen.

3.3 Supply of energy services

The supply of energy services is the result of primary energy inputs that are transformed into energy services by activities and processes.

3.3.1 Sources of primary energy supply. The sources of supply of energy cover all means by which energy can enter or leave the system (other than to meet energy demands). The sources of supply are distinguished by type of energy, cost, origin and environmental characteristics (e.g., sulphur content of coal). The national production possibilities can have an absolute limit or can be available at rising marginal costs.

3.3.2 Energy activities/technologies. The energy activities, transforming energy into energy services, are described through technologies. Three types of technologies are generally distinguished:

1. conversion technologies: load dependent plants generating electricity or district heat
2. process technologies: all other transformation activities, load-independent and environmental technologies
3. demand technologies: all devices consuming energy to meet energy services demands

Environmental activities are represented through technologies such as CO_2 removal, desulphurisation and denitrification, catalytic converters for cars and trucks.

The technologies are characterised by the following information:

1. technical parameters: efficiency of the process, links between inputs and outputs, joint output ratios, etc.
2. capacity parameters: earliest investment date (for new technologies), lifetime of the technology, maximum growth ratio or maximum capacity addition per period, residual installed capacity, bounds
3. cost parameters: investment cost per unit of capacity, fixed maintenance cost, variable costs, delivery costs
4. availability parameters: forced outage, maintenance, etc.
5. environmental characteristics: emission ratios per type of process for the 6 pollutants considered (CO, CO_2, SO_2, NOx, VOC and PM).

3.4 Environmental damage

3.4.1 General approach. To integrate the environmental damage in the modelling framework above, we follow the bottom-up damage function approach developed by the ExternE project. This approach can be illustrated by Figure 11.1 (EC, 1995). It allows to compute a damage per unit of emission.

The damage per pollutant or damage function is modelled as follows within MARKAL/TIMES

$$\mathrm{DAM(env)} = \mathrm{EV}_{\mathrm{coef}}(\mathrm{env}) * \mathrm{EM(env)},$$

where

EM(*env*) are the emissions,

$\mathrm{EV}_{\mathrm{coef}}(env)$ is the damage per unit of emission or the marginal cost per emission under the assumption of a linear damage function; the value per unit of emission is derived from the ExternE results, as explained in the next section.

The sum of the damage-functions per pollutant is added to the objective function and therefore taken into account in the optimisation process. If not included in the objective function, it allows to compute the environmental damage generated by a policy, without feedback into the optimisation process.

As the computations are based on dose response functions which give the incremental damage from air pollution, the results should also be interpreted in these terms, i.e., in terms of the change in total damage compared to a reference year (the base year).

In order to construct the marginal damage associated to a particular emission we need two types of information. First we need information on the transformation and transport of emissions into depositions and concentrations. Second we need information on the damage functions that translate depositions/concentrations into damage and its monetary values.

3.4.2 Coefficients for the transformation and transport of emissions. This step establishes the link between a change in emissions and the resulting change in deposition/concentration levels of primary and secondary pollutants. Because of the transboundary nature of pollutants we need to account for the transport of SO_2, NO_x, VOC and particulates emissions between countries. In the case of tropospheric ozone (a secondary pollutant), besides the transboundary aspect, the relation between VOC and NO_x emissions, the two ozone precursors, and the level of ozone concentration has also to be considered.

Theoretically, the concentration/deposition (IM) at time t of a pollutant ip in a grid g is a function of the total anthropogenic emissions

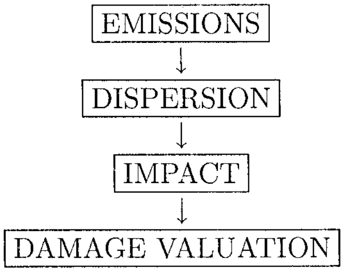

Figure 11.1.

before time t, some background concentration[6] (BIM) in every country c, and other parameters such as meteorological conditions, as derived in models of atmospheric dispersion and of chemical reactions of pollutants:

$$\mathrm{IM}_{\mathrm{ip},g} \equiv \mathrm{im}_{\mathrm{ip},g}(\mathrm{EM}_{p,c}(t' \leq t), \mathrm{BIM}_{\mathrm{ip},g}, \ldots \forall p, c).$$

For the model, the equations are made static and the problem is linearised through transfer coefficients TPC which reflect the effect of the emitted pollutants on the deposition/concentration of a pollutant ip in a specific grid, such as to measure the incremental deposition/concentration, compared to a reference situation:

$$\Delta\,\mathrm{IM}_{\mathrm{ip},g} = \sum_{p}\sum_{c} \mathrm{TPC}_{p,\mathrm{ip}}[g, c] \cdot \Delta\,\mathrm{EM}_{p,c},$$

where $\mathrm{TPC}[g, c]$ is an element of the transport matrix TPC with dimension $G \times C$. In our model the grid considered is a country and deposition/concentration levels are national averages.

The transport/deposition coefficients for SO_2 and NO_x emissions are derived from EMEP budgets for airborne acidifying components (EMEP, 1996) which represent the total deposition at a receptor due to a specific source. Basically, the EMEP model is based on a receptor-orientated, one-layer trajectory (Lagrangian) model of acid deposition with 150 km resolution. Characteristics of the various pollutants and their transportation across countries, as well as atmospheric conditions are taken into account. For particulates, Holland (1997) has estimated country-to-country transfers of primary particulates. His computations are based on a simple model which accounts for the dispersion of a chemically stable pollutant around a source, including deposition by wet and dry processes. To convert deposition into air concentration, use was made of linear relationships estimated by Holland (1997).

Tropospheric ozone is a secondary pollutant formed in the atmosphere through photochemical reaction of two primary pollutants, NO_x and VOC. The source-receptor relationship is not as straightforward as for acid deposition. However, it is recognised (EMEP, 1996; Simpson, 1992) that there is a relatively strong linearity between change in ozone concentration and change in its precursors emissions (both VOC and NO_x), allowing an approximation through linear source-receptor relationships.

It would be useful to include the distinction in the source of emission, for instance between emissions from mobile sources and/or low height

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[6] Resulting from natural emissions and emissions from geographic parts that are not included in the country set.

stationary sources as opposed to high stack sources as it is expected that the deposition of pollutants per unit emitted will be different in each case. However, there is no information available at this moment that allows making such distinction.

3.4.3 Damage parameters and their monetary valuation.

The damage parameters and their monetary valuation are taken from the ExternE project of the European Commission (1997 – 2000). Therefore the approach followed here is entirely based on the framework derived in the project, though at a much more aggregated level. The damage occurs when primary (e.g., SO_2) or secondary (e.g., ozone) pollutants are deposited on a receptor (e.g., in the lungs, or on a building) and ideally, one should relate this deposition per receptor to a physical damage per receptor. In practice, dose/exposure-response functions are related to (i) ambient concentration to which a receptor is submitted, (ii) wet or dry deposition on a receptor or (iii) "after deposition" parameters (e.g., the PH of lake due to acid rain). Following the "damage or dose-response function approach," the incremental physical damage DAM per country is given as a function of the change in deposition/concentration (acidifying components or ozone concentration in the model),

$$\Delta\,\mathrm{DAM}^{c}_{\mathrm{ACID},d} = \mathrm{dam}^{c}_{\mathrm{ACID},d}(\Delta\,\mathrm{IM}_{\mathrm{ip},c}(t),\ldots\forall\mathrm{ip}).$$

The damages categories considered in the model are

1. damage to public health (acute morbidity and mortality, chronic morbidity, but no occupational health effect)
2. damage to the territorial ecosystem (agriculture and forests) and to materials, this last category being treated in a very aggregated way.

The impact on biodiversity, noise or water is not considered, either because there are no data available that could be applied in this study or because air pollution is only a minor source of damage for that category.

For the monetary valuation of the physical damage, a valuation function VAL for the physical damage is used:

$$\mathrm{VAL}^{c}_{0}(t) = \mathrm{val}^{c}_{0}(\Delta\,\mathrm{DAM}^{c}_{0,d}(t),\ldots\forall d).$$

The economic valuation of the damage should be based on the willingness-to-pay or willingness to accept concept. For market goods, the valuation can be performed using the market price. When impacts occur in non-market goods, three broad approaches have been developed to value the damages. The first one, the contingent valuation method, involves asking people open- or closed-ended questions for their willingness-to-pay in response to hypothetical scenarios. The second one, the hedonic price method, is an indirect approach, which seeks to uncover values for the non-marketed goods by examining market or other types of behaviour that are related to the environment as substitutes or complements. The last one, the travel cost method, particularly useful for valuing recreational impacts, determines the WTP through the expenditure on, e.g., the recreational activities.

It is clear that measuring environmental costs at the global level as in this model, raises different problems, which are extensively discussed in ExternE: transferability of the results from specific studies, time and space limits, uncertainty, the choice of the discounting factor, the use of average estimates instead of marginal estimates and aggregation. However, despite all these uncertainties, it is possible, according to ExternE, to give an informative quantified assessment of the environmental costs.

Impact on public health. The ExternE project retains, as principal source of health damages from air pollution, particulates[7] resulting from direct emission of particulates or due to the formation of sulphates (from SO_2) and of nitrates (from NO_x), and ozone. They retain also a direct effect of SO_2 but no direct impact of NO_x because it is likely to be small. Direct damages from VOC are not yet considered here, because the ExternE figures are still at a preliminary stage. The assessment of health impacts is based on a selection of exposure-response functions from epidemiological studies on the health effects of ambient air pollution (both for Europe and the US). They are reported in the ExternE report (European Commission 1997–2000).

For the valuation of the different health impacts, ExternE makes a distinction between morbidity and mortality impacts. The valuation of *morbidity* is based on estimates of WTP to avoid health related symptoms, measured in terms of respiratory hospital admissions, emergency room visit, restricted activity days, symptom days, etc. They are based on an extensive study of the literature on the costs of morbidity, mainly US based. In general the WTP for an illness is composed of three parts: the value of the time lost because of the illness, the value of the lost utility because of the pain and suffering and the expenditure for averting and/or mitigating the effects of the illness. The costs of illness (COI) is measured directly: the actual expenditure associated with the different illnesses plus the cost of lost time (working and leisure time). The other cost components, which are more difficult to evaluate, are measured by

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[7] PM10, i.e., particulates of less than 10 $\mu g/m^3$ aerodynamic diameter, is taken as the relevant index of ambient particulate concentrations.

Table 11.1. Valuation of mortality and morbidity impacts from ExternE (ECU90)

Mortality	
Statistical life	2,730,435
Lost life year	81,000
Acute Morbidity	
Hospital admission for respiratory or cardiovascular symptoms	1,324
Emergency room visit or hospital visit for childhood croup	448
Restricted activity days (RAD)	78
Symptoms of chronic bronchitis or cough	6
Asthma attacks or minor symptoms	31
Chronic Morbidity	
Chronic bronchitis/asthma in adults	84,237
Non fatal cancer/malginant neoplasm	361,000
Changes in prevalence of cough/bronchitis in children	181

CVM methods (for the value of pain and suffering[8]) and models of averting behaviour. When no WTP estimates is available, the COI approach was followed and a ratio of 2 for WTP/COI for adverse health effects other than cancer and 1.5 for nonfatal cancer was assumed.

For the valuation of the *mortality* effect, ExternE uses the "value of life years lost" approach (VLYL), because the E-R functions used are closer to this concept for most health impacts (see Markandya, 1997)[9]. The valuation figures used in ExternE are summarised in Table 11.1.[10]

Combining the impact and valuation data, an estimation of the health damage figure per incremental pollution can be computed for PM10 en PM2.5 (direct and indirect), for SO_2 (direct) and ozone.

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[8] The altruistic cost, i.e., pain and suffering to other people is not included in the ExternE figures.

[9] The VSL estimates are based on studies of individuals with normal life expectancies whereas the pollution impacts for some kinds of mortality were on individuals with much shorter life expectancies.

[10] The latest ExternE figures (1997 – 2000) are expressed in ECU 1995. They were transformed in ECU 1990 assuming a price increase of 20.8% between 1990 and 1995.

Table 11.2. Damage from an increase in air pollution (10^6 ECU90 per 1000 persons)

From an increase of one $\mu g/m^3$ of PM10 and nitrite concentration	0.017120
From an increase of one $\mu g/m^3$ of sulphite concentration	0.028340
From an increase of one $\mu g/m^3$ of PM2.5 concentration and Diesel particulates	0.029225
From an increase of one $\mu g/m^3$ of SO_2 concentration	0.000527
From increase of one ppb of ozone concentration	0.003100

Table 11.3. Damage from an increase in air pollution (10^6 ECU90 per 1000 persons

From an increase of one $\mu g/m^3$ of sulphite concentration	0.0028
From an increase of one $\mu g/m^3$ of nitrite concentration	0.0018

Impacts on territorial ecosystems and materials. Because of the large uncertainty around dose-response functions and the valuation of the damages, it was impossible to derive a damage impact coefficient with a valuation term associated to it for each category of damage. Moreover first results from ExternE showed that they were relatively less important than public health impact: in the first ExternE evaluation they represented approximately 25% of total damage from particulates (direct and indirect). Therefore Holland (1997) computed an average damage cost per person from the ExternE detailed computations to be used as an indicative value

3.4.4 The case of Belgium.

Damage from emissions in Belgium. Combining the figures for the transportation and transformation of pollutants and the figures for the damages, one obtains the damage per unit of emission of a primary pollutant. The distinction can be made between the damage within the country and the damage across the border, generated by the emission of a pollutant in one country. The distinction between domestic and total damage remains approximate, because the geographic location of the source can be important. The estimations for Belgium are given in Table 11.4.

Table 11.4. Damage from emissions in Belgium (10^6 ECU90 per kt emission of pollutant

	Damage in Belgium	Total damage (in Belgium and abroad)
NO_x	0.45	4.83
SO_2	1.50	5.00
VOC	0.05	0.50
PM	4.55	14.54
PM transp (PM2.5)	8.25	24.82

Impact on cost of technologies. To illustrate the order of magnitude of the external cost in total production costs, we give in Table 11.5 a comparison of electricity production costs in 2010 for Belgium (Proost and Van Regemorter, 2001). Costs are divided in three categories: fuel costs, non-fuel costs (investment, operation and maintenance) and external costs (cost of air pollution, noise, greenhouse gases, ionising radiations, etc.).

All costs are expressed before taxes and subsidies. Hence, they represent the opportunity cost for society of producing power rather than something else. Capital costs are translated into costs per kWh by using a maximum expected hours of operation per year. The maximum expected number of hours of operation takes into account the planned and unplanned unavailability of the power plant. For wind and hydro powerplants, the maximum expected number of hours of operation takes also into account the availability of wind or water power. External costs represent the costs that power production imposes on society and that are not included in the fuel, capital or variable costs and are not taken into account by the electricity generators. They include in this case not only the direct effect of operating the power plant but also the indirect effect during construction and due to the extraction and transport of the fuel, i.e., the external cost of the entire life cycle of electricity.

All figures are derived from the ExternE project (1996, 1998, 2000). For greenhouse gases (measured in CO_2 equivalent) we used the middle estimate, with a 3% long-term discount rate, at approximately 18 EURO[11] per tonne of CO_2. The ExternE study also provides external

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[11] This is an estimate based on expected damages due to climate changes in the world. It is close to the marginal cost of reaching the Kyoto CO_2 emission target in Belgium in 2010 in this paper but lower than the cost for later periods with more stringent CO_2 targets.

Table 11.5. Cost of electricity production by technologies in 2010 (2000 EUROcents/ kWh_e)

	Cost (non-fuel)	Fuel cost	Total 1	External cost/ CO_2	other	Total 2
Pulverised coal (USC, 2020)	2.11	1.31	3.42	1.26	0.40	5.08
IGCC	2.55	1.59	4.14	1.54	0.32	6.00
Kerosene gasturbines	4.49	3.89	8.38	1.54	1.96	11.87
Gas gasturbines	4.61	3.20	7.81	0.94	0.62	9.40
STAG power plant	1.12	2.13	3.25	0.62	0.20	4.07
AP600 nuclear (40 years)	1.93	0.99	2.93	0.02	0.07	3.02
MHTGR nuclear (30 years)	3.50	0.64	4.14	0.02	0.07	4.21
Wind turbine onshore, seaside	4.49	0.00	4.49	0.05	0.05	4.59
Wind turbine offshore	5.83	0.00	5.83	0.05	0.05	5.92
Wood gasification — STAG	2.23	4.88	7.11	0.17	0.72	8.01

costs for nuclear electricity generation. We used the estimate over 10,000 years, with 0% discounting, as recommended in the ExternE report.

Table 11.5 presents the cost of electricity production for the main technologies that could be used in 2010. The column "Total 1" accounts for all fuel and non-fuel production costs. In addition, "Total 2" includes external costs. The increase in cost when adding the external cost ranges from 2% for wind turbines to approximately 75% for coal powerplants.

4. Policy scenarios with Belgian MARKAL

4.1 Definition of the policy scenarios

We consider three policy scenarios addressing local air pollution and global warming. The first one focuses on local air pollution only, the second one on CO_2 emission reductions only and the third combines both types of policies. They are compared to a reference scenario in which no environmental policy is imposed, neither for local air pollution neither for CO_2 emission reductions with the exception of the existing regulations on cars and large combustion plants. Also the existing tax policy regarding energy is imposed in the reference scenario considering that these taxes referred mostly to non environmental targets (e.g., congestion, road infrastructure, competitiveness).

For the local air pollution policy only (LAP scenario), we impose an environmental tax on SO_2, NO_x, VOC and particulates emissions equal to the marginal damage (in Belgium and abroad) generated by the pollutant emitted in Belgium, as given in Table 11.4. A more geographically disaggregated model, both at the level of the generation of emissions and at the level of the transformation and transportation of emissions,[12] would clearly enhance the analysis because the damages from air pollution are "location" dependent.

For the global warming policy (GW scenario) we do not use a damage figure for global warming but impose a total CO_2 emission limit on the Belgian energy sector. This cap on emissions corresponds to the EU Kyoto target, translated into a target for Belgium through the burden sharing agreement within the EU. This target consists in reducing the emissions of greenhouse gases in 2008 - 2012 by 7.5% compared to the level of 1990. After 2010, we have assumed that the GHG emissions must continue to decrease at the same rate: in 2030, they must be 15% below their 1990 level. This target is imposed on the CO_2 emissions alone. We also assume that this target has to be met in Belgium and that no tradable permits or other flexible mechanisms can be used to achieve the required reduction in Belgium. The links between the reduction of certain pollutants and global warming, e.g., the cooling effect of sulphur emissions, should be taken into account in a world scale analysis but is less relevant for our country level analysis.

The third scenario, addressing both local pollution and global warming (LAP-GW scenario), is a combination of the two above scenarios. The focus of the comparison of scenarios lies, at this stage, on the mutual impact of the policies and not on the definition of optimal environmental policies or the choice of policy instruments neither on the technological options.

4.2 The scenario comparison

4.2.1 Emission results. A policy that focuses on local air pollution only would mainly decrease PM, NO_x and SO_2 by using extra abatement measures for large combustion plants and by switching from coal to natural gas. The benefit in terms of CO_2 emission reductions exists but is small (-8%, cf. line LAP in Table 11.6).

In 2010, the cap on CO_2 emissions requires an overall reduction of 15% in 2010 (cf. column 1, line GW of Table 11.6). A CO_2 emission reduction only policy would generate an emission reduction of approx-

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[12] In this exercise the country is taken as "one" grid.

Table 11.6. Emissions of different pollutants in 2010 (index with emissions reference scenario = 100)

	CO_2	NO_x	PM	SO_2	VOC
LAP	92	62	45	65	92
GW	85	87	82	84	96
LAP-GW	85	55	37	56	92
Reference	100	100	100	100	100

imately 10 to 15% for the most important local air pollutants (cf. line GW in Table 11.6). This has to do mainly with two factors. First there is an overall reduction of fossil energy use to meet the CO_2 emission cap. Secondly, a GW policy means substitution of coal by natural gas because natural gas is only half as intensive in CO_2 emissions per unit of energy as coal and coal use generates more SO_2 and PM.

Optimising both policies jointly leads to the same CO_2 emissions as a CO_2 only policy because there are (by assumption) no welfare benefits for CO_2 emission reductions beyond the cap. There are however stronger reductions in local air pollutants than in a policy that focuses on local air pollutants only because there is a combined effect of a reduction of energy use (of the order of 15%) and a cleaner energy use.

4.2.2 Scenarios comparison.

In Table 11.7, the first line shows the discounted welfare cost (excluding air pollution damages) of implementing a given policy. We see that the gross cost (before local air pollution benefits) of pursuing local air pollution policies is much smaller than the CO_2 policy. This can be explained by the stringency of the CO_2 emission targets. Combining both policies has a gross cost that is smaller than the sum of the gross costs of the two policies separately.

Table 11.7. Welfare and environmental benefits over the entire horizon (1990 – 2030) (10^6 ECU90) (differences with reference scenario)

	LAP	GW	LAP-GW
Discounted welfare, excluding environmental benefit	−1006.3	−2741.3	−3140.9
Discounted local environmental benefits	2237.5	1351.9	2670.9
Net welfare effect	1231.1	−1389.4	−470.0

The main reason is that CO_2 emission reduction policies also reduce local air pollutants and vice versa.

The welfare impact of the LAP scenario in which an "optimal" local air pollution policy is implemented via emission taxes equal to the marginal damage, tends to indicate that the current Belgian local air pollution policies are too weak, or at least not optimised given the damage figures used in this exercise (damage to Belgium and to its neighbouring countries). A small welfare benefit would not be unexpected as the model we use assumes optimised and fully informed responses by all agents. The net welfare benefit is however too large to be due to model imperfections. This raises questions about the marginal damage estimates of air pollution and/or the efficiency of present air pollution policies. The estimation of marginal damages remains a hazardous exercise and policy makers may have a different view. There are however two reasons why present policies are indeed too weak. First, policy makers use mostly technology regulations and this is a less efficient instrument than emission taxes and at least in Belgium do not cover all sources of local pollution. Second, the local air pollution damages are the sum of domestic damages and damages in neighbouring countries (see Table 11.4). The damages in neighbouring countries will only be taken into account if there is an efficient international negotiation mechanism at that scale. Even if such a mechanism is being put into place at EU there remains an important transaction cost that may hinder the full realisation of all efficiency gains. It should also be mentioned that the tax policy in place also has an impact on the welfare cost of the policy.

The net benefit of a GW policy only is negative, since no benefits from CO_2 emissions reductions are taken into account in the table. The local air pollution gains are large because the marginal air pollution damage per unit of energy used is large when local air pollution policy is not optimised. The local air pollution benefits reduce the total cost of the GW policy by approximately half.

Combining both policy objectives still generates a net cost. The net cost is however smaller than in the GHG only policy because interesting options to reduce local air pollution damage are now fully exploited. The combination of both policies is able to reduce the cost of GW policies by more than half. The local environmental benefits are higher than in the GW policy or the local pollution policy alone.

When we examine the time profile of costs and benefits in Table 11.8 we need to keep in mind two factors. First the CO_2 emission limit decreases over time: in 2010 an emission reduction of 7.5% is required compared to 1990 while in 2030 a reduction of 15% is required. Second less polluting equipments are introduced over time in the reference be-

Table 11.8. Welfare and environmental benefit per period (undiscounted, differences with reference scenario)

		2010	2020	2030
Welfare, excluding environmental benefit (10^6 ECU90)				
	LAP	−324.1	−358.5	−430.6
	GW	−416.9	−1740.4	−5034.4
	LAP-GW	−501.0	−1835.8	−5138.3
Local environmental benefit (10^6 ECU90)				
	LAP	605.8	686.2	821.4
	GW	227.9	548.9	1414.3
	LAP-GW	724.4	996.7	1424.7
Net welfare benefit (10^6 ECU90)				
	LAP	281.7	327.7	390.8
	GW	−189.0	−1191.4	−3620.1
	LAP-GW	223.4	−839.1	−3713.6

cause of the introduction of more stringent emission standards in Europe (e.g., for cars and trucks). This explains that in Table 11.8, the net cost of GW policies increases over time while the net benefits of local air pollution policies increase only slightly. In 2030, the CO_2 emission goals are so stringent that the local pollution abatement benefits are becoming marginal compared to the CO_2 abatement cost.

In Table 11.9 we show the marginal cost of the CO_2 emission reduction constraint. In our model, this is also the CO_2 tax that is needed to attain the emission cap. In the line GW we see that the marginal cost increases over time and this was expected as energy use grows in the baseline and as the emission limit becomes more stringent over time. When both policies are in place, the CO_2 emission tax needed is smaller, especially in the first period. At the end of the horizon (2030) when the local benefits are becoming marginal, the CO_2 marginal costs are very close in both scenarios.

5. Conclusion

As environmental policies are addressing more and more targets covering different domains, the interaction between policies becomes an im-

Table 11.9. Marginal cost of CO_2 reduction (ECU90/ton)

	2010	2020	2030
GW	23.5	66.5	197.7
LAP-GW	6.6	48.3	195.8

portant element in the policy design. This paper examines the interaction between a local air pollution policy and a CO_2 reduction policy with a partial equilibrium model for the energy market MARKAL/TIMES for Belgium, as both pollution are linked to energy consumption and their abatement possibilities are interrelated. The country, here Belgium, faces an absolute emission cap for CO_2 and generates a constant marginal damage from the emissions of four conventional air pollutants. From the simulations with MARKAL/TIMES three main conclusions can be derived.

First, the results indicate that present local air pollution policies in Belgium are too weak considering the damage estimates used here. This means that an improved local air pollution policy can generate important net benefits.

Secondly, a policy focussing on CO_2 emissions only has important ancillary air pollution benefits but they do not fully outweigh the costs of the GW policy. The local air pollution benefits reduce the total cost of the GW policy by approximately one-third but this level of the side benefit depends partly on the local policy in place. Here in the case of Belgium they are relatively important because of the weak local pollution policy.

Third, implementing (and optimising) GW policies and local air pollution policies jointly is able to reduce the cost of GW policies by about 50%. Here again the benefit from a joint optimal policy is partly due to the non-optimality of the local pollution policy.

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